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Supporting Order Capturing in Mass Customization

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STAGE CONFIGURATION FOR CAPITAL GOODS

SUPPORTING ORDER CAPTURING
IN MASS CUSTOMIZATION

BY
BJØRN CHRISTENSEN

DISSERTATION SUBMITTED 2019

AALBORG UNIVERSITY
DENMARK

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CV

Bjørn Christensen was born in Sønderborg, Denmark. With a background as an auto mechanic, he graduated from Aarhus School of Marine and Technical Engineering in 2013, followed by a MSc degree in Production Systems from Aalborg University in 2015. Afterwards, he worked as a supply chain analyst at Vestas Wind Systems for two years before starting as an Industrial PhD fellow. His PhD is conducted in collaboration between Vestas Wind Systems and the Department of Materials and Production at Aalborg University, co-funded by the Innovation Fund Denmark.

ENGLISH SUMMARY

Managing product variety is a key challenge and opportunity in today's manufacturing industry. Increased variety of products offered to the marketplace is a result of various factors, e.g. growing wealth in society, increased manufacturing productivity, globalization of markets and emergence of new local needs and competitors, as well as rapid advancements in technology and materials. Consequently, customers on one hand request products satisfying individual needs, and companies on the other hand utilize product variety, customization, and even personalization as a main source of competitiveness and differentiation in the marketplace. However, offering variety comes at a cost, as internal complexity often increases with increased product variety, e.g. in terms of increased design/development time and resource usage, reduced productivity in manufacturing, higher material and inventory cost, as well as difficulties in information and data management. To address this dilemma of producing a vast range of products while at the same time reducing costs and internal complexities, "Mass customization" is a well-known business strategy. One of the central elements in succeeding with a mass customization strategy is to assist customers in selecting the right combination of product characteristics that satisfy their needs, while at the same time ensuring high quality and efficiency in product realization and order fulfillment internally within the company. This is commonly achieved by implementing a product configurator.

Product configuration systems are expert systems, usually involving a software tool that can support customers in choosing a set of predefined product characteristics, creating the basis for manufacturing the product. Thus, given a set of components, their properties, a description of how they can be combined, and input on the desired product specification, the task of the configurator is to construct a product that satisfies all given constraints and requirements formalized in the product model. During the last 20 years, product configurators have become an integrated part of e-commerce, well-known as web-based configurators ranging from configuring cars and boats to shoes and apparel. These configuration systems are applied for consumer goods and are built on similar architectures i.e. a user interface where the user can query the knowledgebase containing expert knowledge about a product and an inference engine providing user advice. While product configuration has been widely applied with success for consumer goods, several challenges still exist for capital goods.

Capital goods are generally considered as one-of-a-kind products, where development and configuration are closely interlinked, the main order winner is customer return on investment (ROI), and order specifications are gradually committed in order capturing processes. All of these conditions substantiate the need for efficient product configuration, however, prevailing challenges exist in terms of the integration between the expert system and the product lifecycle management system, release of partially developed product families, multiple specification points, and inclusion of

supply chain information when inferencing the optimal product for the customer. Generally, these challenges have received limited attention in research compared to product configuration for consumer goods, leaving conceptualization and application of product configuration in capital goods industries largely unexplored.

Therefore, the objective of this PhD thesis is to develop the concept of stage configuration and establish knowledge on how this approach can support order capturing in the capital goods industry. The overall research approach is the design research methodology, where research builds on both theory and practice and focus on understanding the problem, formulating objectives and hypotheses that guide descriptive and prescriptive studies for developing, and evaluating a solution. Consequently, a mixture of specific research methods is embraced in this thesis e.g. case research, quantitative modelling and simulation, and action research. The industrial collaborator of this thesis, Vestas Wind Systems, serves as the case company for the research.

The research presented progresses in three parts, each addressing a specific research question. Collectively, the thesis covers 6 appended research papers. The first part of the presented research (Paper 2 and 3) addresses the question: How can product configuration be organized in stages to support engineering and supply processes, thereby enabling staged configuration? The contribution in this part includes a conceptual framework for stage configuration that consists of a stage-wise alignment between solution space modelling and order specification, as well as a step-wise modelling process in a product lifecycle management system. The second part (Paper 3 and 5) addresses the question: How can modelling of configurable product platforms support product configuration in stages? For this part, a classification framework is proposed for modelling product families for stage configuration depending on the product architecture. The framework is tested in combination with a product lifecycle management system and a commercial configuration software. The third part of the thesis (Paper 4 and 6) addresses the question: How can configuration be applied to optimize order profitability considering supply chain constraints? In this part, an optimization model is proposed incorporating product configuration and supply chain decisions, as well as investigations of how a reconfigurable supply system can potentially enable this. Collectively, the results of each three parts of this PhD thesis contribute with increased knowledge on stage configuration, thereby creating a solid foundation for its implementation in the capital goods industry.

DANSK RESUME

I vor tids globale produktionsmiljø udgør produktvarians både en betydelig udfordring og mulighed. Øget produktvarians er generelt set et resultat af adskillige faktorer, f.eks. voksende samfundsvelstand, øget produktivitet i fremstillinsindustrien, globalisering af markeder, fremkomst af nye lokale behov og konkurrenter samt vedvarende udvikling af nye teknologier og materialer. Virksomheder søger ofte at øge deres konkurrenceevne via differentiering i form af øget produktsortiment, kundetilpasning og endda personalisering af produkter for dermed at imødekomme kundernes individuelle behov. Det at tilbyde produktvarians har dog en pris, idet kompleksitet internt i virksomheden ofte øges, f.eks. i form af forlænget design/udviklingstid og øget ressourceforbrug, reduceret produktivitet i produktionen, højere omkostninger til materialer og lagerbeholdning, samt vanskeligheder i information og datastyring. For at løse dilemmaet med at producere et stort udvalg af produkter, mens omkostningerne og den interne kompleksitet holdes nede, er "Mass Customization" blevet anvendt og foreslået som en forretningsstrategi. Et af de centrale elementer i at lykkes med Mass Customization er at hjælpe kunderne med at vælge den rigtige kombination af produktegenskaber, der tilfredsstiller deres behov, og samtidig sikrer høj kvalitet og effektivitet i produktgennemførelse og ordreopfyldelse. Dette opnås ofte ved at implementere en produktkonfigurator.

Produktkonfigurationssystemer er ekspertsystemer, der oftest involverer et softwareværktøj til at støtte kunder i at vælge et sæt foruddefinerede produktegenskaber, som derved skaber grundlaget for fremstilling af produktet. Givet et sæt komponenter, deres egenskaber, en beskrivelse af hvordan de kan kombineres, og input til den ønskede produktspecifikation, er konfiguratorens opgave at konstruere et produkt, der opfylder alle givne begrænsninger og krav, der er formaliseret i produktmodellen. I løbet af de sidste 20 år er produktkonfiguratorer blevet en integreret del af e-handel, bedre kendt som webbaserede konfiguratorer, der anvendes til at konfigurere alt lige fra biler og sejlbåde til sko og beklædning. Konfigurationssystemer anvendes ofte til sådanne forbrugsvarer og består af en brugergrænseflade, hvor forbrugeren kan forespørge en vidensbase indeholdende ekspertviden om et produkt, og en inference-engine der efterfølgende forsyner forbrugeren med svar på forespørgslen. Produktkonfiguration er med succes, og i vid udstrækning, blevet anvendt inden for forbrugsvarer, mens der stadig er betydelige udfordringer indenfor for konfigurering af kapitalvarer.

Kapitalvarer betragtes oftest som "one-of-a-kind" produkter, hvor udvikling og konfiguration er tæt sammenkoblet og hvor ordrer bliver vundet ved at tilbyde kunderne det største afkast på deres investering, samt hvor ordrespecifikationer gradvist bliver besluttet i løbet af salgsfasen. Alle disse forhold underbygger behovet for en effektiv produktkonfiguration. Der findes dog udfordringer med hensyn til integrationen mellem produktkonfigureringsystemet og product lifecycle

management (PLM) systemet, navnlig frigivelse af delvist udviklede produktfamilier, flere specifikationspunkter i forsyningskæden og inkludering af forsyningskædeinformation, når virksomheden konfigurerer det optimale produkt for kunden. Generelt har disse udfordringer fået begrænset opmærksomhed i forskning sammenlignet med produktkonfiguration for forbrugsvarer, hvilket efterlader konceptualisering og anvendelse af produktkonfiguration i kapitalvareindustrien stort set uudforsket.

Formålet med denne afhandling er derfor at udvikle et koncept for fase-inddelt konfigurering og etablere viden om, hvordan denne tilgang kan understøtte ordregenerering for kapitalvarer. Den overordnede forskningsmetode er Design Research Methodology, som bygger på både teori og praksis og fokuserer på forståelsen af problemet, formulering af mål og hypoteser, der kan styre beskrivende og foreskrivende undersøgelser til udvikling og evaluering af en løsning. Som følge heraf er en blanding af specifikke forskningsmetoder anvendt, f.eks. case research, kvantitativ modellering og simulering og action research. I denne ph.d.-afhandling er den industrielle samarbejdspartner Vestas Wind Systems, som fungerer som den primære case-virksomhed.

Forskningen præsenteret i denne afhandling er inddelt i tre dele, der hver især vedrører et specifikt forskningsspørgsmål. Samlet set dækker afhandlingen 6 vedlagte forskningsartikler. Den første del (artikel 2 og 3) behandler spørgsmålet: Hvordan kan produktkonfiguration organiseres i stadier for at understøtte design og forsyningsprocesser og derved muliggøre en faseinddelt konfiguration? Bidraget i forhold til dette spørgsmål inkluderer et konceptuelt rammeværk for fasekonfiguration, der består af en trinvis tilpasning mellem konfigurationsmodellering og ordrespecifikation, samt en trinvis modelleringsproces i et produktlivscyklusstyringssystem. Den anden del af afhandlingen (artikel 3 og 5) behandler spørgsmålet: Hvordan kan modellering af konfigurebare produktplatforme understøtte produktkonfiguration i faser? I denne del foreslås et rammeværk til modellering af produktfamilier med henblik på opnåelse af fasekonfiguration, afhængigt af produktarkitekturen. Den tredje del af afhandlingen (artikel 4 og 6) behandler spørgsmålet: Hvordan kan konfiguration anvendes til at optimere ordrerentabilitet mens forsyningskædebegrænsninger bliver taget i betragtning? I denne del foreslås en optimeringsmodel, der indeholder beslutninger om produktkonfiguration og planlægning af værdikæden, samt undersøgelser af hvordan et rekonfigurerbart forsyningssystem potentielt kan understøtte dette. Samlet set bidrager resultaterne af denne afhandling med øget viden om fasekonfiguration, hvorved der skabes et solidt fundament for dens implementering i kapitalvareindustrien.

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Most importantly, I would like to thank my girlfriend Ass. Prof. Ann-Louise Andersen. I could not have completed this PhD project without your support, feedback and least of all patience. We have talked about my project many times during the last three years, which always helped me in the right direction. You have motivated me to continuously improve the research and provided me vital advice on all parts of this project, both professionally and in regard to the research process.

Thank you.

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2. Bjørn Christensen, Thomas D. Brunoe and Kjeld Nielsen, 2018. *A Conceptual Framework for Stage Configuration.* In Moon, I., Lee, G.M., Park, J., Kiritsis, D., von Cieminski, eds. Advances in Production Management Systems. Production Management for Data-Driven, Intelligent, Collaborative, and Sustainable Manufacturing. Springer Proceedings of the International Conference, APMS 2018, pp- 101-109.

3. Bjørn Christensen, Thomas D. Brunoe and Ann-Louise Andersen. *Product Configuration Modelling in PLM Environment using Configuration Ontologies.* In review for Journal of Engineering Design.

4. Bjørn Christensen, Thomas D. Brunoe and Ann-Louise Andersen. *Concurrently Optimizing Product Configuration and Order Allocation for Capital Goods Considering Supply Chain Constraints.* In review for CIRP Journal of Manufacturing Science and Technology.

5. Bjørn Christensen, Thomas D. Brunoe and Ann-Louise Andersen. *Modelling configurable product platforms: an empirical study in the capital good industry.* In review for Journal Computers in industry.

6. Bjørn Christensen, Ann-Louise Andersen, Khaled Medini, Thomas D. Brunoe, 2019. *Reconfigurable Manufacturing: A Case-Study of Reconfigurability Potentials in the Manufacturing of Capital Goods.* In: Ameri, F., Stecke, K.E., von Cieminski, G., Kiritsis, D, eds. Advances in Production Management Systems. Production Management for the Factory of the Future. Springer Proceedings of the International Conference, APMS 2019, pp. 366-374.

RELATED PAPERS BY THE AUTHOR NOT INCLUDED IN THE THESIS

7. Khaled Medini, Ann-Louise Andersen, Thorsten Wuest, Bjørn Christensen, Stefan Wiesner, David Romero, Ang Liug, Fei Tao, 2019. *Highlights in Customer-driven Operations Management Research*. Procedia CIRP vol 81, pp. 399-404.

8. Ann-Louise Andersen, Thomas D. Brunoe, Bjørn Christensen, Mads Bejlegaard, Daniel. G. H. Sorensen and Kjeld Nielsen, 2020. *Tailored Reconfigurability: A Comparative Study of Eight Industrial Cases with Reconfigurability as a Key to Manufacturing Competitiveness.* In: Lyes Benyoucef eds. Reconfigurable Manufacturing Systems: From Design to Implementation. Springer Series in Advanced Manufacturing, pp. 209-245.

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CHAPTER 1. INTRODUCTION

The need for product configuration systems can be credited to major tendencies in technical, social and economic development, and was initially triggered by the 1st and 2nd industrial revolutions. From the beginning of the 1st industrial revolution in 1760 to its end in 1840 (Schwab 2017), increased productivity was sparked by mainly employing new technologies into manufacturing processes, thereby establishing a growing total factor productivity (TFP) (Jensen 1993). As a result, improved living standards led to an increase in population, growing with 670% from 1800 to 2018[1]. The industrial revolutions further led to a general growth in wealth, which increased the world´s gross domestic product (GDP) per capita with 1.053% from 1870 to 2016[2]. The simultaneous growth in population and GDP resulted in higher wealth and increased buying power. Another significant contributor was the division of labor, recognized in 1776 as one of the main driving forces of increased productivity (Smith 1776). However, it was not until the end of the 2nd industrial revolution that division of labor was extensively utilized in industrial manufacturing. Most noticeably was the invention of the assembly line popularized by Ford in 1912, which utilized specialized labor to perform small and simple manufacturing operations, thereby increasing efficiency dramatically (Roser 2016). From 1909 to 1923, Ford managed to increase the production of the Ford T model by 18.755%, while in the same period lowering costs as well. He did so by only producing a narrow and similar range of products by means of standardized assembly operations and division of labor into specialized tasks (Roser 2016). The Model T was outdated in 1927 and Ford had to develop the newer Model A to satisfy customer requirements. This was a major turning point in industrial manufacturing, which emphasized that customers, due to their increased wealth, would not be satisfied with low priced standard products. Rather, they required the newest technology and products that to a greater extent covered their specific needs. Thus, Ford had to change the assembly lines to enable the production of the new Model A, but as every machine was optimized to manufacture the Model T, it took Ford 6 months to reconfigure the assembly lines with no production in that period (Roser 2016). It became apparent that companies must not only frequently renew and offer different products, but also ensure an efficient and fast transition to the supply of new product models. The tendency of increasing product offerings was in 1933 investigated and summarized under the concept of product differentiation, which is the process of differentiating product functionalities to target specific customer segments (Chamberlin 1949). During the end of the 1940s, marketplaces were significantly expanded due to globalization and international trade. To stay competitive, suppliers were continuously developing and adapting their product

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[1] https://ourworldindata.org/world-population-growth

[2] https://ourworldindata.org/economic-growth

offerings to meet foreign and domestic requirements, leading to yet again an increase in product variety. The world´s export as part of GDP grew from 4.16% in 1945 to 24.24% in 2014[3], indicating a dramatic expansion of international trade and product variants, especially taking into consideration that the previous 69 years of export dropped from 10.75% to 4.16%[3]. In the following years, from 1985 to 2015, patent applications per million residents grew with 169%[4], indicating an immense pace in technology developments and further fueling the demand for frequent and rapid new product introductions (NPI). Until the late 1980s, companies either adapted Ford´s competitive strategy and pursued a cost leadership position, benefiting from the effects of economies-of-scale, or employed a differentiation strategy embracing product variety to satisfy specific customer requirements, but at a higher cost (Porter 1983).

1.1. BACKGROUND

To address the industrial dilemma of producing a vast range of products at a cost near mass production, Davis first coined the concept of "Mass customization" in 1989 as a business strategy to offer more value to customers by increasing the variety of traditional standard products, thereby customizing them individually to suit each customers' requirement (Davis 1989). The interest in mass customization grew rapidly during the 1990s and 2000s with scholars researching the topic from multiple perspectives, aiming at defining central capabilities and methods for achieving mass customization (Fogliatto, da Silveira et al. 2012). It is today commonly acknowledged that to become a successful mass customizer, companies must possess fundamental capabilities: 1) "solution space development", being able to efficiently develop products with a variety that corresponds to customer requirements, 2) "robust process design", being able to supply a high and constantly changing product variety at a low cost, and 3) "choice navigation", the ability to support customers in configuring or choosing the specific products matching their requirements (Salvador, De Holan et al. 2009).

1.1.1. CHOICE NAVIGATION

A central element of mass customization is the high and rapidly changing variety of products offered to customers. The most common way to manage and navigate in this variety is by using a product configurator (Nielsen, Brunoe et al. 2013, Pine et al. 1993). Product configuration systems usually involve a software tool, the configurator, from where customers can choose a set of predefined product characteristics, creating the basis for manufacturing the product (Trentin, Perin et al. 2011). Product configuration systems represent a kind of expert systems, branching

[3] https://ourworldindata.org/trade-and-globalization

[4] https://ourworldindata.org/grapher/patent-applications-per million

from knowledge-based systems which originate from artificial intelligence (Russell, Norvig 2016). One of the first expert systems was MYCIN, developed in the early 1970s. MYCIN was used to identify bacterial infections and blood cluttering diseases, and to recommend antibiotics and dosages adjusted for the patient´s body weight (Russell, Norvig 2016). MYCIN was reported to perform as well as senior doctors and considerably better that junior doctors. The identification of diseases and corresponding treatments was achieved by requiring the user to answer a series of yes/no questions, which would then result in a list of likely diagnoses with related drug treatments (Shortliffe, Davis et al. 1975). MYCIN used a simple backwards chaining inference engine and a knowledge base approximately consisting of 450 rules representing knowledge from doctors and experts within the specific medical field. Expert systems was shortly after adapted in industry as well, where R1 (XCON) was developed by the Digital Equipment Corporation in early 1980s, as the first commercial product configuration system to support customers in navigating increased product variety for new VAX computer systems (McDermott 1982). XCON saved the Digital Equipment Corporation an estimate of $40 million a year and was largely based on the same system architecture as MYCIN. In MYCIN, the user answered a series of questions to describe symptoms, while in XCON, the user answered a series of questions describing product requirements. VAX computer systems were inferred by the inference engine based on customer requirements in the same manner as treatments were inferred based on the described symptoms in MYCIN. The knowledge provided to MYCIN came from doctors, while in XCON, the knowledge came from product experts, see Figure 1.

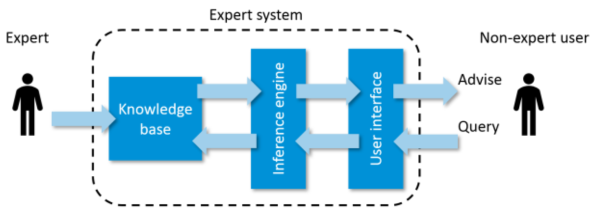

Figure 1. Expert system architecture

The main architecture of an expert system is largely the same today as it was when MYCIN was developed (Hvam, Mortensen et al. 2008). The architecture consists of a knowledge base, an inference engine, and a user interface. An expert is supplying the expert system with domain specific knowledge. The knowledge is formalized in the knowledge base to support inference. A non-expert user can query the knowledge provided by the expert through the user interface. The inference engine retrieves knowledge from the knowledge base, based on the user query and presents an advice to the user (Haug, Hvam et al. 2012).

Due to the promising results of using product configuration systems to navigate and manage product variety for VAX computer systems, its implementation spread to other industries as well, reporting additional benefits such as reduced delivery times, reduction of resources for making quotations, improved quality of quotations, improved on-time delivery, etc. (Hvam, Haug et al. 2013). Improved inter-firm coordination and strengthening of ties to customers are additional results of applying product configuration, thereby increasing effectiveness and efficiency of order acquisition and fulfillment processes (Forza, Salvador 2002b, Forza, Salvador 2002a). For instance, implementing configurators for complex infrastructure systems for data centers and cement production plants have shown promising results in reducing delivery times, reducing production costs, improving the capability of introducing new products to the marketplace, and facilitating internal knowledge sharing (Hvam 2006a, Hvam 2006b). Other reported benefits are; improved concurrent engineering activities (Aldanondo, Rouge et al. 2000), right-the-first-time configuration and efficient manufacturing of complex products (Slater 1999), and standardization and formalization of quotation processes and product knowledge representations (Ladeby 2009). The investigated benefits have been reported from implementing configurators in various companies and are extended and verified by major survey studies on product configuration across industries (Trentin, Perin et al. 2011, Haug, Hvam et al. 2011, Salvador, Forza 2004).

To achieve these benefits, the application of expert systems in product configuration has evolved and improved through development of additional capabilities, such as recommendation technologies, reasoning, graphics, diagnosis, need elicitation, knowledge representation, configuration management, conceptual modelling, etc. (Zhang 2014). With these improvements, configurators are today among the most successfully applied artificial intelligence technologies in industry and are widely employed to navigate the physical and functional structures of product platforms and families (Blecker, Abdelkafi et al. 2004). Product configuration does today broadly consist of; the product, the configuration task, the product model and the configuration system (Oddsson, Ladeby 2014). The product specification is the output of the configuration task and represents the final instance of the product, which often is referred to as the product variant or the product configuration (Oddsson, Ladeby 2014). A product is composed of an arrangement of components and functions inferred from the product model by the configuration task. Given a set of components, their properties, a description of how components can be combined, and input on desired product specification, the task of the configuration is to configure a product that satisfies all given constraints and requirements formalized in the product model (Mittal, Frayman 1989). The product architecture is established during new product development and is translated into a product family model defined as an abstract representation of the product's entities, its structural composition and the rules on how the entities can be combined through the product's functional and physical design (Hvam, Riis et al. 2002). The last entity is the configuration system, sometimes referred to as the product configurator. However, the configuration system and the configurator are two different entities. The product configurator allows the user to navigate valid combinations of product characteristics and arrange them to create a product variant under a given set of constraints restricting how entities and their properties can be combined (Haug, Hvam et al. 2010). The configuration system is a much broader term used to describe a system with configuration capabilities, where the configurator in part of that system (Brunoe 2008). After completing the configuration process and configuring the variant, the completed bill of materials (BoM) is used in manufacturing and business processes to transform order specifications from information to physical products and deliver them to customers.

During the 2000s, configurators became an integrated part of e-commerce and was made available to consumers through the internet (Blazek, Partl et al. 2014), making configuration systems a popular and mainstream way to navigate product variety (Su, Liao et al. 2009). Today's configurators are popularly known as web-based configurators enabling consumers to customize a vast variety of goods, ranging from cars, boats and houses to beers, t-shirts and watches[5], se Figure 2.

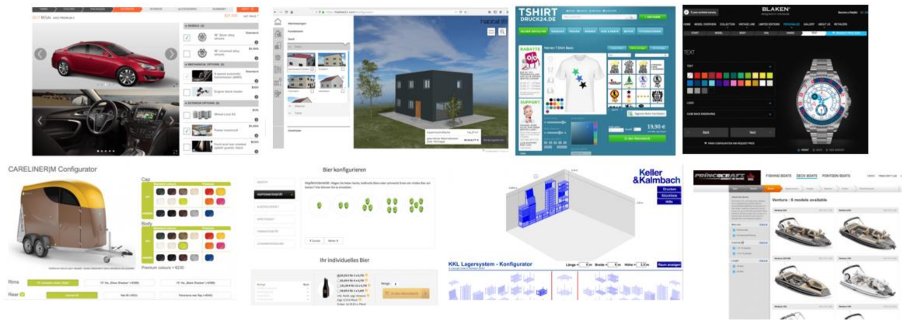

Figure 2. Selection of web-based configurators

Configuration systems for consumer goods are mainly built on the same architecture as the early expert systems, namely with a user interface where the user can query the knowledgebase containing expert knowledge about a product and an inference engine providing user advise (Franke, Piller 2003). However, this architecture is not always sufficient for configuring capital goods, which will be elaborated in the following sections.

1.1.2. SOLUTION SPACE DEVELOPMENT

The product variety navigated through product configuration systems are created and defined during solution space development. Companies offering great product variety by applying a mass customization strategy often fulfill customer requirements from developing platform-based product families with a modular product architecture (Mikkola 2006). A product platform consists of *a "set of sub-systems and interfaces*

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[5] www.configurator-database.com

that form a common structure from which a stream of derivate products can be effectively developed and produced" (Meyer 1997). This definition suggests that a large range of differentiated products can be developed from a collection of common components, processes, knowledge, people and relationships, thereby gaining low-cost benefits from economies-of-scale, while suppling a vast range of products to diverse market segments (Robertson, Ulrich 1998). Market segments are targeted with product families derived as part of the product platform and share related product variants with similar functional structures and subassemblies (ElMaraghy 2009, Jiao, Simpson et al. 2007). To design product platforms and families supporting mass customization, companies must deploy a modular product architecture which allows configuration of commonly shared building blocks into a vast range of distinct final product variants (Tseng, Jiao 1996). With modular product architectures, companies can employ one-to-one relations between product characteristics and physical components, standardize component interfaces and increase the availability of combining different product functions (Ulrich 1995). The design of independent subsystems with standard interfaces further enables a modular product development process, where modules are developed instead of entire products, entailing more rapid and cost-efficient release of product functionalities to market segments based on resource reusability and parallel/concurrent development (Sanchez, Mahoney 1996). The product development process is the central organ in solution space development and governs all activities and decisions in designing the modular platform-based product architecture (Cooper 1990, Krishnan, Ulrich 2001). The stage-gate approach to product development was first proposed in the early 1980´s as a normative guide for product managers to ensure that crucial steps in new product introduction were not overlooked (Cooper 1983). In 1990, the formalization of gates was introduced with a consolidation and refinement of stages (Cooper 1990). The third generation of the process later evolved to using overlapping stages as "fluid" stages with "fuzzy" or conditional go/no go decision gates (Cooper 1994). Developing product architectures has continuously matured to be an integrated part of product lifecycle management (PLM), which appeared in the late 1990s as a means to collectively manage all information related to the product throughout its life (Stark 2015). PLM systems have in previous research proven capable of managing the development of modular product architectures by handling multiple physical and functional product structures, visualization of multiple architectural views, governing interfaces, and quantifying and communicating the status and progress of product developments (Bruun, Mortensen et al. 2015). As most product information is generated through product development processes from the perspective of marketing, organizations, engineering design and operation management, PLM is today widely used in practice for introducing new products to the marketplace (Krishnan, Ulrich 2001).

There are various reasons for increasing offered product variety in companies, such as requirements for new product functionalities, diverse regional demands, and differences in market needs and certifications (ElMaraghy, Schuh et al. 2013). New technologies drive increased product variety as well, as new product features can distinguish products to attract more buyers and thereby secure increased market shares and economic benefits. This can only be achieved with wider offering of choices, more differentiation of product features, and increased possibility for customization to increase customer value. However, increased product variety is not necessarily equal to increased customer value nor necessarily beneficial for companies. Along the introduction of mass customization in industries, the term mass confusion arise arguing that consumers often are confused about which product functionality to select in the configuration process to satisfy their needs (Huffman, Kahn 1998). An entire research area has been established around this challenge, namely the paradox of choice, which points out that an increasing number of choices generally is desirable to increase the freedom to achieve satisfaction, but paradoxically also create paralysis, regret, opportunity costs, escalation of expectation and self-blame (Schwartz 2004). Capabilities in sales configurators have to some extent proven beneficial in avoiding this paradox, specifically in terms of avoiding offering more product variety in the attempt to increase sales, while actually suffering loss of sales (Trentin, Perin et al. 2013). Companies operating mass customization as their business strategy also experience challenges with increased product variety. An exploratory survey discloses major issues in increased material and manufacturing costs when using methods of assembling core product modules and material processing to create customization (Ahlstrom, Westbrook 1999). Increasing commonality through a modular product architecture can often result in increasing material costs due to over-specified designs, compared to customer demand. However, increased material costs must be neutralized by lower manufacturing costs, capitalizing on producing and purchasing more similar product modules. Thus, while modular product platform architectures have proven useful in offering great variety from a common set of product modules, they do not necessarily ensure cost efficiency. Rather, cost efficiency is ensured by supply chain processes.

1.1.3. ROBUST PROCESS DESIGN

Increasing product variety most often entails increasing internal variety in business processes. Business processes must therefore be designed to handle the increased variety, as is the case of designing product architectures. Product variety management is applied to manage variety in products, while supply chain management often is used to manage variety in processes.

Supply chain management generally includes eight main business processes reaching from suppliers to end-customers; 1) customer relationship management, 2) customer service management, 3) demand management, 4) order fulfillment, 5) manufacturing flow management, 6) procurement, 7) product development, and 8) returns (Lambert, Cooper 2000). All business processes have in previous research been identified to impact the effectiveness of product variety management, especially manufacturing flow and demand management (da Cunha Reis, Scavarda et al. 2013).
Manufacturing flow management has been approached through the concept of

changeable manufacturing, defined as the ability of the manufacturing systems to accomplish economically, early, and foresighted adjustments of structures and processes on all levels in response to changes (ElMaraghy, Wiendahl 2016). Such changes could for instance be product changes, variant changes, or changes in production volume. Both flexible and reconfigurable manufacturing systems have been proposed as changeable manufacturing systems for mass customization, but should be carefully applied depending on the degree of product customization and the volume being manufactured (ElMaraghy, 2005). The flexible manufacturing system (FMS) was the first type of changeable manufacturing system proposed in research and has been extensively discussed as an integrated system with pre-build-in flexibility, generally capable of suppling a wide range of possible products with minimum effort in adapting to diverse processing requirements (Sethi, Sethi 1990, Browne, Dubois et al. 1984, Upton 1994). However, with computerized numerical controls (CNC) machines and robots as main enablers of FMS, common drawbacks of the implementation of these systems in industry were large capital investments, unsatisfactory capacity utilization, too high functionality, and high system cost (Koren 2010). Thus, in the 1970s-90s, these systems were in many cases reported unsuccessful (Koren 2010). In the light of optimality, agility, waste reduction, quality and lean, reconfigurable manufacturing systems (RMS) was introduced in the late 1990s as an intermediate system paradigm between dedicated manufacturing systems (DMSs) for mass production and FMSs. An RMS is defined as a manufacturing system designed for rapid change in structure, hardware, and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in the market (Koren, Heisel et al. 1999). Thus, an RMS possesses exactly the capacity and functionality needed, exactly when needed, in contrast to both FMS and DMS.

Mass customization often employs the concept of delayed differentiation, where standard product modules are produced based on a forecast, stored as semi-finished goods and then assembled into a customer-specific finished product when receiving a customer order (Su, Chang et al. 2005). Delayed differentiation, also referred to as postponement, was first proposed to increase efficiency in marketing processes by delaying the differentiation of products to the last possible point, where demand presumable would be more predictable (Alderson 1950, Bucklin 1965). Postponement later became a main enabler of mass customization, i.e. as a supply chain strategy incorporating product design, process design, and supply chain management, focusing on optimizing the division between the cost-efficient production of standard modules and the customization processes, a split also referred to as the customer order decoupling point (CODP) (Yang, Burns 2003, Van Hoek 2001). Studies on postponement have reported efficiency improvements, such as more responsive service levels, reduced lead time, reduced inventory buffers, lifetime cost reductions and fewer production changeovers (Lee, Tang 1997). CODP is the point of differentiation where the customer interacts with the supply chain to commit product specifications (Yang, Burns et al. 2004). Knowing which specifications to commit rely on how well customers can match available product characteristics with customer requirements in the sales configurator.

1.1.4. SUMMARY

Product configuration as a means to support choice navigation in mass customization was initially developed to manage and navigate product variety for consumer goods. Later, product configurators evolved with mass customization into a customization process including solution space development and robust process design for supply chain processes, see Figure 3.

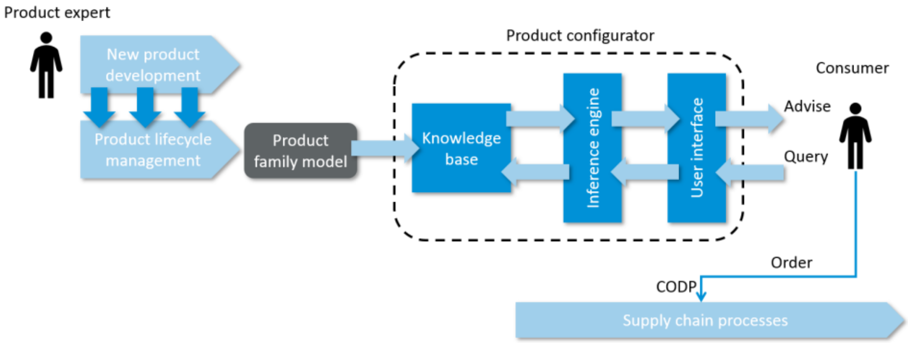

Figure 3. Consumer goods customization process

The outcome of the solution space modelling process is typically a product family model, enriched and governed by a PLM system. The product family model is represented in the configurator's knowledge base allowing consumers to configure product variants. When a configuration has been completed, an order is committed at the CODP to be produced/assembled. Although product configuration have mainly been focused on consumer goods, companies and scholars have increasingly recognized the potentials of using product configurators for capital goods as well (Levandowski, Jiao et al. 2015, Shamsuzzoha, Kankaanpaa et al. 2011, Son, Lee et al. 2011). To mention a few, Petersen et al. (2007) described the case of a shipyard sub-supplier, Caputo & Pelagagge (2008) reported on configurators used in process vessel shipyards, Zhu et al. (2011) investigated lift equipment, Kristianto et al. (2013) explored ship engines and power generators, and Lewandowski et al. (2015) focused on jet engine parts. However, as the consumer goods industry and the capital goods industry are fundamentally different, challenges such as longer order horizons, gradual determination of product specifications, increased product complexity, engineer-to-order (ETO) and co-configuration between supply chain and configurator, makes traditional configuration system largely inapplicable, requiring alternative approaches in the capital goods industry (Christensen, Brunoe 2018).

1.1.5. MAIN CHALLENGES FOR CONFIGURATION OF CAPITAL GOODS

Capital goods can be defined as any type of asset used to produce income, consumer goods, or services, and are generally considered as one-of-a-kind products with high complexity and requirements for substantial capital investments (Veldman, Alblas 2012). Such complex products generally have a significant amount of interdependent components with fuzzy design and supply boundaries, as well as requirement and process uncertainties that entail an unclear relationship between cause and effects (ElMaraghy, ElMaraghy et al. 2012). In Table 1, some of the main differences between the capital goods and the consumer goods industry are summarized.

Table 1. Configuration: Capital goods vs. consumer goods

	Capital goods	Consumer goods
Supply strategy	A mixture of Engineer-to-order, Make-to-stock, Make-to-order and Assembly-to-order	Either Make-to-stock, Make-to-order or Assembly-to-order
New product introduction	Order capturing process in parallel with new product introduction	Order capturing begins after new product introduction
CODP	Multiple specification points	One CODP
Specification horizon	Long order and specification horizons	Short and with no option to revisit the specification
Specification flexibility	Multiple changes to the specification	Firm when committing
Order winner	Main order winner is return on investment	Main order winner is customer preferences
Complexity	High product and application complexity	Typical moderate configuration complexity
Role of Supply chain	Part of order capturing	Order execution
Lifetime	Long, several decades	Typical short, ranging from fast moving consumables to durables up to 5 - 10 years

In the capital goods industry, the order is specified iteratively during a long order horizon, often while the specified product family is being developed. The result is commitments of partly specified orders with partly specified product characteristics, postponed to be decided in later stages of the specification process. The point of specifications is related to the traditional view on CODP, however, without placing a complete order through the configurator and initiating order specific manufacturing processes (Rudberg, Wikner 2004). Rather, at the specification points, the customer only commits parts of the order and postpones the remaining configuration decisions to later stages. Because the order horizon is long and the specification process can be performed in parallel with the new product development process, the order is subject to multiple changes, with the purpose to either comply with new constraints or to exploit new opportunities. In the capital goods industry, the main order winner is to maximize return on investment (ROI) for the customer considering the income generated from the product and the cost of operation during its entire lifetime. The supply chain therefore becomes a significant contributor to reducing the cost, while providing the optimal solution within given sets of constraints, such as delivery time, local content and supplier and product preferences. The last major difference is the complexity, which generally appears higher in capital goods industries with a higher degree of ETO due to the effort of optimizing the product to individual operating environments (Yujun, Chunqing 2008). Consumer goods such as cars, shoes, computers etc. are rarely subject to configuration outside the solutions already available in the configurator, while for capital goods companies, supporting ETO configuration is a competitive advantage. Thus, the consumer goods customization process (Figure 3) cannot directly be transferred to the capital goods industry, but rather must be adapted as depictured in Figure 4.

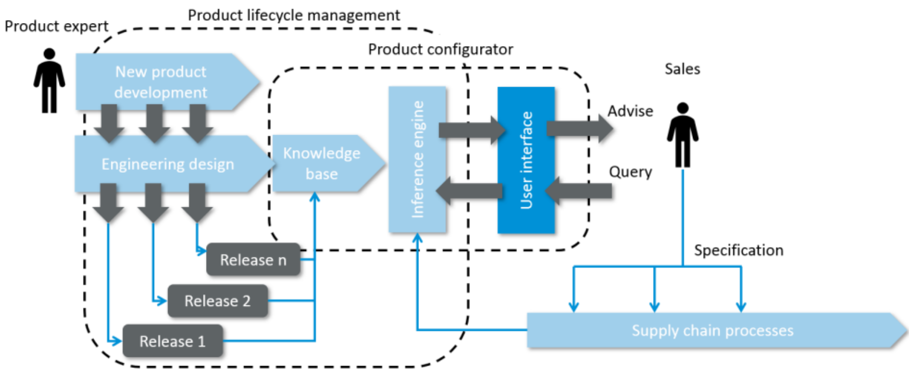

Figure 4. Capital goods customization process

The main difference between the customization process in the consumer and capital goods industries are the integration between the product configurator and the PLM system, release of partially developed product families, multiple specification points, and supply chain information being included when inferencing the optimal product for the customer.

1.2. STATE OF THE ART

To address the configuration challenges in the capital goods industry, scholars have suggested a stage-wise approach to order capturing, specification, and configuration modelling. Staged configuration was first mentioned by Czarnecki (2005) as a novel concept for specializing feature models in a stepwise approach, where configuration choices available in each stage would be defined by a separate feature model. The process of determining a feature is therefore performed in stages, where each stage eliminates other configuration choices and yields a specialized feature model where part of it is a subset of the feature model in the previous stage. A configuration stage can be characterized by three parameters; 1) timing of different phases in the product lifecycle e.g. requirements engineering, product design, testing, etc., 2) different roles in the supply chain being responsible for different parts of the configuration, and 3) components in systems subject to configuration are deployed in different contexts and therefore also in different stages of the specification process. Shortly after introducing the concept of stage configuration, Zeng (2006, 2007) further explored stage configuration from a value chain perspective and investigated how buyers could postpone the full order specification of features to as late as possible, so that producers can utilize partial order information to maximize supply chain responsiveness. One of the main conclusions was that product features/attributes can be divided into three categories depending on the feature’s sensitivity to market fluctuations, the available capacity and cycle time for the feature, and its dependency to other features and supply processes. For features subject to market variations, low available capacity and low dependencies, nonlinear programming can be used to optimize the postponement of committing relevant features to as late as possible, given quantity, capacity and lead-time constraints. Stage-wise postponing the commitment of features in the order capturing process imposes certain challenges when using a product configurator to configure product variants. Two of the challenges were researched by Brunoe (2008), which focused on costing and product family modelling. Costing is vital in the order capturing process as a starting point for pricing and offer acceptance. However, with stage-wise specification of product modules, it is not possible to use the traditional approach of adding the costs of each individual module to a final total cost. The iterative ranking method was therefore suggested to act on historical configuration and cost data to create a linear model predicting costs for future configurations, using as few significant features as possible. Product family modelling can be implicitly or explicitly specialized over time and are conveniently modelled using unified modelling languages (UML). Specialization reduces the solution space on multiple abstraction levels and supports configuration on different levels of detail, as well as at different times.

Instead of modelling complete product families, Kristianto (2015) suggested that the modelling should be confined to a system level, where key building blocks and interfaces between components should be maintained. The system level configurator could then propose high-level solutions, while leaving the details unspecified. The unspecified design is then managed by engineering change management in stages as the specification process progresses. In Figure 5, essential aspects related to stage configuration from previous research are summarized.

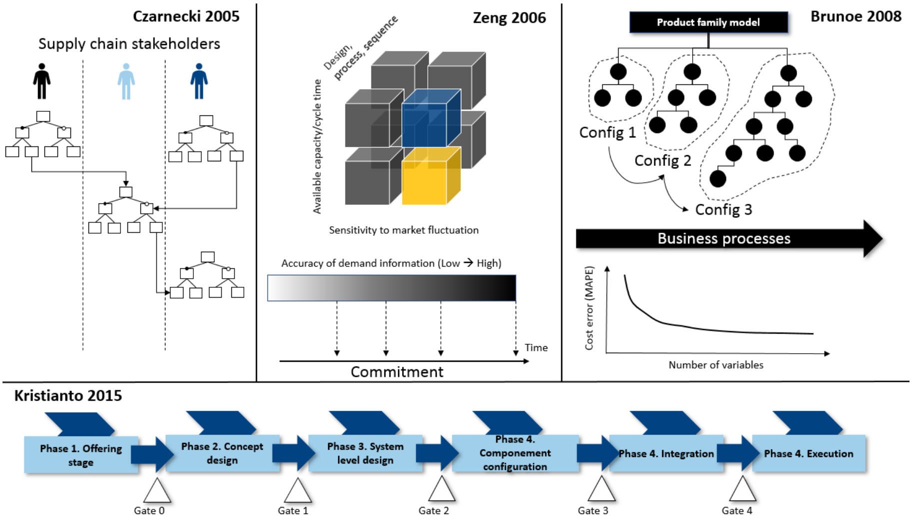

Figure 5. Main aspects in previous research related to stage configuration

By comparing the background on the three capabilities for mass customization with the characteristics of product specification in the capital goods industry, provided by previous research, the following research areas is further explored: 1) product configuration, PLM and product development, 2) product and process configuration and optimization, and 3) product platform modelling for configuration.

1.2.1. PRODUCT CONFIGURATION, PLM AND PRODUCT DEVELOPMENT

When companies bring new products to the marketplace, the development process is most often conducted as a stage-gate approach (Jiao, Simpson et al. 2007). The newest version of the stage-gate process is the so-called triple A system (Adaptive and flexible, agile, accelerated) (Cooper 2014). The triple A system is highly inspired by SCRUM product development, suggesting multiple iterations throughout the development process with the purpose of diversifying the maturity between different parts of the product, which means the development project can be conducted in multiple stages at the same time. As the norm in the capital goods industry is to offer products while they are being developed, there is a need for the configuration modelling process to be aligned with the stage-gate product development process, which then also should be conducted in stages.

A sequential procedure for developing product models and implementing these in configuration systems was proposed by Hvam et. al. (1999). The procedure consists of seven-stages describing how to develop a product model from process and product analysis to implementation and maintenance. The procedure applies the product variant master (PVM) or the product family master plan (PFMP) method followed by object-oriented modelling to describe both classification and composition in the product model (Harlou 2006, Mortensen, Hvam et al. 2010). However, the procedure does not describe the relationship to stage-gate product development and how the PVM or PFMP methods can be applied in a PLM system, which are often used to govern and manage new and current product designs. PLM is defined as the systematic collection of activities for integrating and managing all product related information and processes through the entire lifecycle of a product, from initial idea to disposal (Stark 2015). As all product related activities are governed by the PLM system, so is its development and modelling activities. An example of product knowledge representation in PLM is the novel Property-Driven Development and modelling method, which distinguishes between characteristics and properties in the configuration model to increase the control and speed of new designs, making them more transparent to stakeholders (Weber, Werner et al. 2003). Previous research in product configuration for PLM systems, however, mainly focuses on configuration management, especially engineering change management (ECM) (Srinivasan 2011). Configuration management (CM) has been reported multiple times in research as implementation of CMII standards in PLM systems to enhance process excellence and improve ECM in relation to configuration modelling (Wu, Fang et al. 2014). Further research has developed methods to integrate supply and design applications into the configurable product model in PLM systems. Examples of this include assembly models (Gao, Bowland et al. 2002) and computer aided design models (Sung, Ritchie et al. 2011). Configuration ontologies have proven useful when advancing product configuration research from a conceptual level (Soininen, Tiihonen et al. 1998a) to generic software tools (Orsvärn, Axling 1999) and to an integration with enterprise resource planning (ERP) systems (Haag 1998). Configuration ontologies have although mainly focused on ontology language, such as web ontology language (OWL) and semantic web rule language (SWRL) to represent configuration knowledge (Yang, Dong et al. 2008). Both languages are primarily used to build configuration models in the open-source Protégé software system, where java execution system shell (JESS) is used as inference engine (Sanya, Shehab 2014). Few researchers have proposed ontologies for automated stage configuration using the before mentioned language (Boskovic, Bagheri et al. 2010), but they remain largely inapplicable for specification processes and PLM systems.

1.2.2. PRODUCT AND PROCESS CONFIGURATION AND OPTIMIZATION

Research on optimizing the co-configuration of processes and product selection has mainly been divided in separate parts i.e. process configuration and product selection optimization. Zhang (2007) proposed a systematic methodology for process platform-based production configuration for mass customization, aiming at supporting production planning in configuring existing operations and processes by exploiting similarities in product and process families. The optimization part of the methodology aims at outputting the optimal routing which can produce the product with the lowest production cost and shortest lead time. Aldanondo and Vareilles (2008) determined product configuration as a constraint satisfaction problem and extended the methodology towards production routing and requirement configuration, entailing a consolidated and coherent configuration model consisting of a product model, a routing model and an operating model. Based on this study, Pitiot (2013, 2014) proposed a two-step approach to concurrently optimize product selection and the production planning of the product. The purpose is to avoid time-consuming iterations between product configuration and production planning, which is currently the case in many companies. In that sense, after a product is fully configured and defined, planning often comes up with a delivery schedule that is too late, too expensive, or in other ways does not comply with customer requirements, thereby needing modifications to the configuration, thus causing iterations in the process. As the objective of the study is to optimize product performance, production costs and delivery time, the result of the configuration task is represented as a set of possible compromises in the form of a pareto front rather than a single solution that aggregates criteria.

Frutos (2004) suggested a decision support system containing an integer linear programming (ILP) approach to achieve optimized product selection. The ILP approach seeks to maximize the utility of a specific configuration being subject to design and financial constraints, based on customer's wishes and preferences. Customer's preferences are given as weights and are linked to attributes of the product. Based on the weights, the product selection is optimized for customer utility and provides a corresponding combination of components offered by the supplying company. Bin Li (2006) applied a different perspective on product selection optimization, as he suggested to optimize the selection of specific parts from components in a product model and assemble an end-product while minimizing production costs and lead time. By minimizing costs and lead time, Bin Li attempted to incorporate supply chain consideration into product selection and configuration. Hong (2010) also used weights to describe the importance of product attributes for different customers and further extended this for the corresponding manufacturing processes. Then, by using co-evolutionary genetic programming, an optimization of product design and process planning could be achieved based on individual customer requirements in one-of-a-kind production.

1.2.3. PRODUCT PLATFORM MODELLING FOR CONFIGURATION

Research in product platform modelling has mainly focused on the design of product platforms and less on how to model them for variant configuration (Pedersen 2010). However, on a conceptual level several approaches have been suggested to close this gap in literature (Shafiee, Hvam et al. 2017). Product platform modelling for configuration has been approached on a conceptual level and is commonly acknowledged as consisting of a physical and functional structure. Jiao and Tseng (1999) developed a methodology to represent a product's architectural design with the purpose of rationalizing product development for mass customization. Felfernig and

Friedrich (2001) applied UML to construct a conceptual configuration model and applied it for debugging the knowledge base of a configuration system. Harlou (2006) developed the PFMP method to represent and manage product variations through architectural composition and applied it in multiple industrial applications. Hvam and Mortensen (2008) further extended the PFMP method to the PVM concept, formalizing a part-off and kind-off structure. PVM has been fully or partly applied in several different companies with success (Hvam 2004, Haug, Hvam et al. 2009). One objective of each of the mentioned methodologies is to transfer product knowledge into a configuration system, so the users can navigate the solution space and generate physical product variants and functional specifications. The physical part of the configurable product platform is often represented by a generic bill of material (GBoM), which contains the modelling of entire product families in one single structure (Hegge, Wortmann 1991, Erens, Wortman 1996). The generation of a specific BoM from the GBoM can be achieved by specifying the desired functions of the product. The functions are mapped to the physical structure from where each sub-assembly is selected and arranged in the configured end-product (Jiao, Tseng et al. 2000). The functional structure is often represented using multiple knowledge representation methods, such as constraints (constraint satisfaction problems), feature models, descriptive logic, answer set programming (ASP), etc. (Hotz, Felfernig et al. 2014). However, these methods are rarely used in commercial ERP, PLM, and configuration software systems. Rather, the representation methods in these systems are often more user friendly, such as conditional statements, decision tables and arithmetic constraints (Tidstam 2014).

1.2.4. GAP IN LITERATURE

Product configuration and mass customization are generally well covered in literature. However, when reviewing the two research domains in relation to the capital goods industry, challenges emerge which are not previously addresses, as the traditional applications have mainly focused on consumer goods. Research on product configuration in the capital goods industry has been conducted from different perspectives, but rarely in relation to stage-wise committing order specifications through a product configuration system during long order horizons considering supply chain constraints. Thus, a gap can be identified for the conceptualization and application of stage configuration, which is summarized below.

1) Configuration knowledge representation and processes have been subject to numerous studies in previous research. The application of these studies is often within a custom-made prototype configurator system, a commercial standalone configuration software system or in an ERP system. Thus, there are very few case specific studies on implementing product configuration in PLM systems aligning knowledge representation with main PLM processes, such as product development and engineering design. The research is especially scarce for capital goods, where the solution space constantly evolves, and changes must be offered in the early stages of

new product development. Ontologies have proven useful in clarifying entities and relationship in complex research domains. In the configuration domain, previous research on configuration ontology has mainly focused on ontology language and is limited on applicability and implementation. Researchers have proposed generic conceptual configuration ontologies, but without a specific application and sparsely in relation to PLM systems. Thus, configuration ontologies have not yet been investigated thoroughly and applied in a PLM setting, combining solution space modelling with new product design processes.

2) To optimize product selection in the capital goods industry, the specification process must consider the product family model, customer preferences, the application environment and supply chain processes simultaneously. A vast body of knowledge has been provided by previous research on optimizing the configuration offered to customers. Additional studies have also researched the co-optimization of product configurations and supply processes, further including customer preferences. The research in optimizing product selection in the capital goods industry has sparsely been addressed in combination with production and demand allocation in a global supply network, considering resource and customer constraints and the application environment in an integrated model.

3) Despite extensive efforts in modelling configurable product platforms applicable for configuration systems, current research is scarce in providing a tangible classification on when and how different methods can be used to support stage configuration. The modelling methods in state-of-the-art are not aligned with new product development nor the need to stage-wise specify the order. Finally, the relationships between product architectures, product platform modelling and stage configuration are not empirically supported in previous research.

1.3. THESIS OBJECTIVE

From the introduction and review of literature in the previous Sections, it is evident there has been a trend towards growing product variety and complexity since the first industrial revolution. A well-recognized competitive strategy to manage product variety is Mass Customization. However, traditional mass customization approaches have mainly been deployed and researched for the consumer industry, leaving specific challenges in the capital goods industry unsolved, especially in the area of navigating the solution space during the process of specifying a customer order. Order specification is fundamentally different in the capital goods industry, as products are specified in stages during long order horizon closely integrated with supply chain processes based on a continuously evolving product platform model. Therefore, the overall objective for this thesis is:

To develop the concept of stage configuration and establish knowledge on how this approach can support order capturing in the capital goods industry

The objective is inferred from the identified gap in literature and aims to further develop the concept of stage configuration in relation to product configuration. The objective statement further scopes this research to focus on the order capturing process in the capital goods industry.

1.3.1. RESEARCH QUESTIONS

This thesis addresses the research objective by answering three research questions (RQ). The research questions further frame this research and elaborate on the research objective. Each research question is addressed in the six appended papers as shown in Figure 8. RQ1 covers the establishment of the concept of stage configuration by investigating how configuration modelling and specification can be divided into stages and aligned with new product development processes in a PLM system. Establishing the stage configuration concept constitutes the foundation for answering the remaining RQs.

RQ1: How can product configuration be organized in stages to support engineering and supply processes, thereby enabling stage configuration?

The second RQ further details the product configuration and development part of the stage configuration concept established through RQ1. The focus in on aligning product architectures with modelling methods to generate as much of the product's physical composition as possible during product variant configuration.

RQ2: How can modelling configurable product platforms support product configuration in stages?

The third RQ focuses on the order specification processes in the stage configuration concept and its relationships with constraints in the supply chain. There are multiple levels in the order specification process where product selection can be optimized, however, an integrated approach is needed in order to avoid violation of supply chain constraints.

RQ3: How can configuration be applied to optimize order profitability considering supply chain constraints?

1.4. INDUSTRIAL PARTNER

The research presented in this thesis is funded by the Innovation Fond Denmark and Vestas Wind Systems. The research project was conducted in collaboration between Vestas Wind Systems and Aalborg University. Vestas is the main case contributor and a suitable environment for conducting research in relation to the research gap presented in Section 1.2.4. In relation to the applicability of Vestas as a case for this research, various indicators can be viewed in Figure 6.

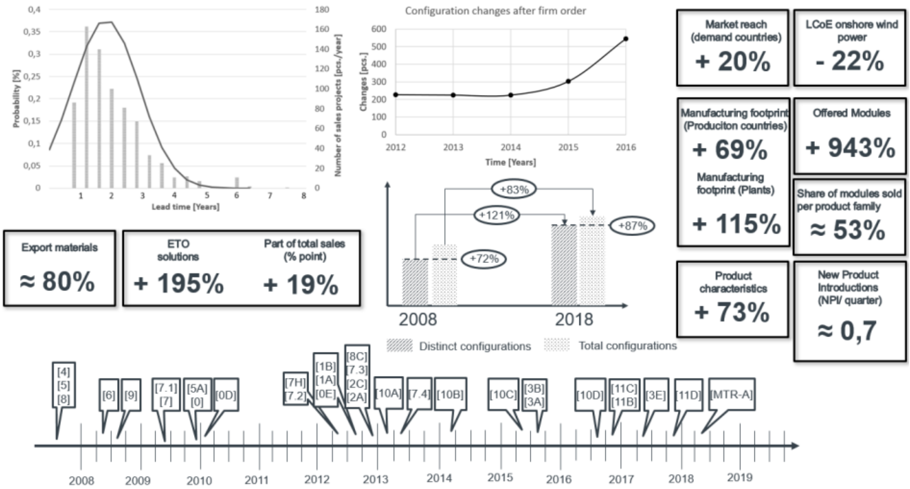

Figure 6. Product variety and specification indicators in the case company

In the case company, the number of sold configurations has increased by 83% in the last 10 years. The vast majority of sold configurations are not sold in more than one order each year. Each order is therefore trending towards having its own distinct configuration, increasing from 72% of annual sales to 87% in the last 10 years. Configurations in the company consist of product modules, which can be combined into a complete product variant within a given set of constraints. The offering of these distinct modules has increased by 943% in 10 years, indicating a significant expansion of the offered solution space. The modules are further divided into product families, where only 53% of the modules are sold. Another indicator of product customization is the increase of ETO configurations. ETO configurations must distinctively be evaluated, designed, tested and prepared in the supply chain before offering them to individual customers, as they are product variants not offered as standard configurations. In the last 10 years, ETO configurations have increased by 195%, resulting in an increase of 19% of total annual sales. The configurations are highly influenced by the frequency of changes to the specification, which are increasing significantly. The changes to a configuration happen more and more frequently indicating a greater volatility and uncertainty in the specification process. A main contributor is the long order lead time, which can range up to seven or eight years. However, 80% of the orders are executed between 1 to 3 years. For the last 10 years, the export level has been steady around 80%, while the market reach has increased with 20%. The export level has remained the same mainly due to an expansion of the manufacturing footprint by 69%, and by increasing the number of manufacturing plants with 115% during the last 10 years.

The main order winner in the capital goods industry is ROI. In the energy industry, this corresponds to levelized cost of energy (LCoE), which is the cost of producing energy in the entire lifecycle of an acquired asset. In the onshore wind industry, the LCoE has generally dropped by 22% in the last 7 years. To stay competitive in industries where the market continually reduces LCoE or increases ROI, it is crucial to provide the optimal configuration to maximize the generated income. Lastly, new technologies and products are frequently introduced to the marketplace, as shown in the timeline at the bottom of the Figure 6. Numbers represent major introductions and letters represent minor. The timeline does not consider continuous implementations of changes to both major or minor product introductions.

Advancing the concept of stage configuration is relevant for Vestas in terms of addressing increased product variety in the following ways: 1) reducing frequent changes to product specifications by allowing step-wise commitments of specifications, 2) offering product families during new product development by stage-wise modelling the configurable product platform model, 3) increasing competitiveness on LCoE by including supply processes in order optimization, and 4) improving the management of a rapidly increasing product portfolio though a stage-wise integrated modelling process.

CHAPTER 2. RESEARCH DESIGN

The central notion in the objective statement of this thesis is "to establish knowledge". Knowledge attains different roles dependent of which research it is being acquired through. For basic research, knowledge is established by performing experimental or theoretical work to increase understanding of underlying phenomena and observable facts without any particular application in mind. For applied research, new knowledge is created having a specific practical aim or objective and is acquired by doing original investigations in practical settings. Lastly, experimental development is systematic work drawing on existing knowledge to create additional knowledge, directed to producing or improving new products and processes (OECD 2015). The research presented in this thesis adapts both applied research and applied experimental development as main research forms to improve specific areas in the case company. This means, new innovations or improvements as a result of this research must seek to be applied in the case company while obtaining the research objective.

2.1. PHILOSOPHICAL KNOWLEDGE POSITIONING

Before beginning the attempt to establish knowledge, the concept of knowledge must first be defined and positioned in the context of this research. A popular and dominant definition of knowledge is provided by Plato, proposing that the concept of knowledge can be defined as "justified true belief" (JTB) (Ichikawa, Steup 2001). In order to create, develop and establish new knowledge, a reasonable consensus is that research must be conducted. Research is defined as the process of formally collecting and analyzing information to increase knowledge on a topic or an issue (Creswell, Poth 2007). Incorporating the definition of knowledge and research, with the objective statement of this thesis acts as the starting point for clarifying the philosophical position of the research design and for selecting a methodology and methods to answer the research questions. The objective statement can therefore be elaborated as:

"Develop the concept of stage configuration through a process of formally collecting and analyzing information to establish new justified true beliefs on how stage configuration can support order capturing in the capital goods industry"

The above elaboration of the objective statement must be further explored to describe the process, including how information is formally collected and analyzed, and how justified true belief should be understood in this thesis. Providing answers to these questions further entails explorations of the concept of knowledge, aiming at its positioning and contextualization. Secondly, a research paradigm must be inferred from the philosophical knowledge positioning to further determine the appropriate research methodology (process) and methods (formally collecting and analyzing data and information).

The first element of the JTB theory is justification. If someone wants to acquire knowledge, the person must be justified in believing something is true. For instance, a hunch is not justified to be true. Having good reasons for believing something is true strongly relates to the methods used to collect data, reliability of the data source, and the analysis of the data. Consider for example a case where a man looks at the clock to know what time it is (Ichikawa 2009). He observes the time to be 3pm and concludes that he now knows the time is 3pm. He uses an observation method to observe the time shown by the clock, which is a widely acceptable and reliable way to know the time. However, what he did not know is that the clock is broken and only by chance happens to be right at that time. This is called a Gettier case, where someone is justified in believing something is true, but the person does not really know, because the premise for the justification is wrong (Gettier 1963). For example, the man looking at the clock will not know the time if he looks at it 5 minutes later, because it is broken, and it just happens to be right when he observed it the first time.

Establishing knowledge from the perspective of JTB would be immensely difficult in applied research because of the volatility and ambiguity in real case scenarios. Even if it was possible to find objective justification on how stage configuration can support order capturing in the capital goods industry through collecting and analyzing data using scientific methods, it would be very difficult to know for sure the Gettier case would be avoided. A different perspective on knowledge is therefore needed in this research. Two theories are selected as more appropriate views om knowledge in this research. The first is causal theory. Causal theory adjusts the JTB theory by substituting justification with appropriate causal connections, while keeping true belief (Goldman 1967). Causal theory argues that someone does not need justification to know something, as long as knowledge was caused in the correct way with causal relations going back to the fact (Steiner 1973). A causal relation could for example be a researcher interviewing an employee in an organization on whether a method has improved the execution of a certain business process. The fact that the execution has been improved is causally linked through the implementation of the method, via the employee to the researcher. The researcher now knows the method has improved the process execution without operating the process or observing the execution personally. However, the problem with this example is that, the employee makes a direct empirical observation of the process and forms a belief about it but is unaware of external factors that make the truth of that belief extraordinary lucky. If the process is actually running worse 99% of the time but happens to run better when the employee observes it, it by chance happens to run better. This means, the researcher forms belief in a way that is unreliable. The second theory solves this problem by introducing reliabilism. Reliabilism forms beliefs from a reliable belief-forming process, acknowledging that beliefs or processes of reliability do not need to be total or absolute (Vogel 2000). Thus, perception, or a particular belief formed by perception count as reliable, despite the fact that perception, or particular beliefs can go wrong under certain extraordinary circumstances. This possesses a crucial question in reliabilism, namely which belief-forming methods are reliable. Not all methods can reliably be used to acquire knowledge, as it depends on which type of knowledge is being acquired and the context of which it is gained (Goldman, Beddor 2016). Now that the approach to justification and truth has been established, the final component of the JTB theory must also be established to clarify whether the created knowledge is believable. This discussion will position the research paradigm and provide a definition on how knowledge should be understood in this thesis.

2.2. RESEARCH PARADIGM AND POSITIONING

Believing only makes sense if it is attached to an individual. Therefore, believing something is true can be a question of subjectivity depending on how a person perceives facts and how arguments are legitimized to be acceptable. (Nonaka, Peltokorpi 2006) A person's beliefs can be framed through a paradigm, which explains how coherent theory formation represents an overall worldview shared by a certain community i.e. a research community in the context of this thesis. Various perspectives on research paradigms exist, such as skepticism vs. positivism, realism vs. relativism, internalist vs. externalist, however, an important classification of contrasts is between the positivist paradigm and the constructivist paradigm (Croom 2009, Guba, Lincoln 1994). In the positivist paradigm, the researcher usually tests theories or describes experiences by using observations and measurements to predict and control forces that surround us, aiming at producing verifiable and generalizable facts (O'Leary 2017). Knowledge is therefore believed to be a universal truth to everybody and can be obtained through pure reasoning, as reality is a true construct external to the researcher (Croom 2009). In the constructivist approaches to research, the research intent is to understand human experience, suggesting truth to be socially constructed by how participants understand the situation being studied (Mackenzie, Knipe 2006). Constructivists therefore believe that individuals' backgrounds and experiences have a vital influence on observations, analyses, and research results. In other words, truth is seen as dependent on the individual. In the continuum in-between the positivist and constructivist paradigm are the pragmatic paradigm. The pragmatic paradigm is fundamentally different than positivist and constructivist, as it rejects the idea that the meaning with research is to describe, represent or mirror truth and reality (Yvonne Feilzer 2010). Pragmatism rather discusses knowledge as a tool for prediction, problem solving and action, emphasizing the practical applications of ideas and their testing through human experience. Justification of knowledge in pragmatism is viewed as a derivative of causal relationships between beliefs and should be evaluated based on how efficiently it explains and predicts a phenomena, as opposed to how accurately it describes an objective truth (Morse 2016). The research presented in this thesis adapts the pragmatic research paradigm, due to the following reasons:

1) Justification: The research problem is investigated through a real-life case, in real time and is accordingly highly complex and context-dependent, requiring multiple participants in both acquiring and evaluating research results.

Justification in this environment can be achieved in a reliable way by clarifying causal relations from the practical application, through the research solution, participants, to the researcher.

2) Truth: The truth in pragmatism can be both objective or socially constructed by participants. However, truth is not the sole objective for knowledge creation in pragmatism, rather knowledge should be created to support research in practical applications. This view on knowledge is well-suited for applied research.

3) Belief: Whether knowledge in pragmatism is practically applicable or not is subject to an assessment either by the researcher directly or through participants' experience. The assessment is based on research results generated by investigations in practical cases. Conclusions on whether the new knowledge is believable or not is evaluated by the researcher based on the results.

By adapting the pragmatic research paradigm and relying on the notion that a reliable belief-forming process with causal relationships, back to the fact, must be present to create knowledge, this research adapts Turban and Frenzel's (1992) definition of knowledge: "*Knowledge is information that has been organized and analyzed to make it understandable and applicable to problem solving and decision making"*. Moreover, pragmatists largely avoid the issues related to truth and reality by focusing on solving practical problems open to empirical inquiries. In that sense, pragmatists are free of restrictions imposed by the positivist and constructivist paradigm, which usually dictates quantitative and qualitative methods to establish truth (Yvonne Feilzer 2010). Instead, pragmatists view the measurable world as made up of layers, some objective, some subjective, or a mixture of the two (Dewey 1958). In order to translate this perspective into methodology and finally method selection, it is essential to figure out how these layers can be measured and observed. To do so, pragmatists use quantitative methods for some aspect of the phenomenon in question and qualitative method for others (Yvonne Feilzer 2010).

2.3. DESIGN RESEARCH METHODOLOGY

Mixed methods are used when a research objective cannot be answered using one single method. This often occurs if complex phenomena need to be explored on both a macro and a micro level or where mechanisms, associations and risks must be explored and documented simultaneously (Morse 2016). The motivation for using mixed methods is present in this research, as the complex phenomenon of stage configuration must be developed on both a macro level, i.e. concept and process level, and on micro level, i.e. configuration modelling and product specification level. Additionally, this research emphasizes the exploration of different aspects of stage configuration, such as order capturing, configuration development and alignment, re-configurable supply etc. To govern this kind of research, a methodology that can embrace both qualitative and quantitative methods is needed.

Multiple application-oriented research methodologies are capable of performing both qualitative and quantitative methods. However, as the objective statement clearly dictates, the research methodology must further include the ability to govern the development of artifacts as well as their implementation to conclude on the generated knowledge. Artifacts in this research should not only be understood as the concept of stage configuration, but also processes, frameworks and tools to support the concept. Implementation should be understood as the descriptive and prescriptive design and application in practice. Additionally, this research is mainly characterized as applied research, emphasized through the research questions and the pragmatic view on knowledge creation, both founded on further developments of existing theories. Based on this, Design Research Methodology (DRM) is selected as the overall research methodology (Blessing, Chakrabarti 2009). DRM is a relatively young, but well-recognized research methodology, which builds on a combination of theory and practice with utility as the main goal. Design research differs fundamentally from more conventional inductive theory building and hypothetical-deductive theory testing research approaches, as it seeks to 1) explore new solution alternatives to solve problems, 2) explain the explorative design process, and 3) improve the problem-solving process. Thus, the DRM focuses on understanding the problem and formulating objectives and hypotheses that guide descriptive and prescriptive studies for developing and evaluating a solution.

Applying a DRM framework suggests that research initially should draw on design problems from both theory and practice. Then, literature should be reviewed in order to develop a hypothesis on how practice can be better supported, from which the research problem should be defined, and a solution developed. Finally, the solution should be applied in practice, evaluated, and documented. In details, it guides activities in the research stages, and distinguishes between the use of descriptive and prescriptive studies for developing a solution. For each of the stages, DRM contains a set of recommended basic means and main outcomes. In the following, each stage is explained and subsequently summarized in Figure 7.

• **Research Clarification:** this initial stage of DRM is concerned with finding evidence to support the assumptions of the research, and formulating the research goals, hypotheses, and problems. In this stage, preliminary literature reviews and analyses should be conducted in combination with investigations in practice, in order to formulate a number of more detailed research questions to address.

• **Descriptive Study:** in this phase, empirical studies are conducted in order to increase understanding of the research problem. The intention of this stage is to identify success factors for meeting the goals, and to prepare for developing support that addresses these factors. In this phase, initial research related to the research questions is conducted, in terms of exploratory studies and investigations related to creating knowledge on how to develop and apply stage configuration to support configuration of capital goods. The case company will be the primary entity for these investigations.

• **Prescriptive Study:** in this phase, the understanding of the success factors gained in the preceding phase is used to develop artefacts that meets the objectives. The research questions are further investigated in this phase, where an actual development of solutions is made, in terms of designing methods and theories for configuration modelling of product platforms, conceptualizing stage configuration, increasing system flexibility to accommodate variety and approaches to optimize product selections and its association with the supply chain. The researcher will be directly involved in developing and implementing research in practice by e.g. contributing to the development of configuration modelling practices in PLM systems to support stage configuration. As such, Vestas will serve as a "lab for experimentation", in order to perform the prescriptive study.

• **Descriptive Study II:** this phase deals with empirical studies to understand the use and impact of the developed artefacts, and it in relation to applicability and usefulness. In this research, the outcome of the developed and implemented stage configuration concept is analyzed and validated in relation to the research questions.

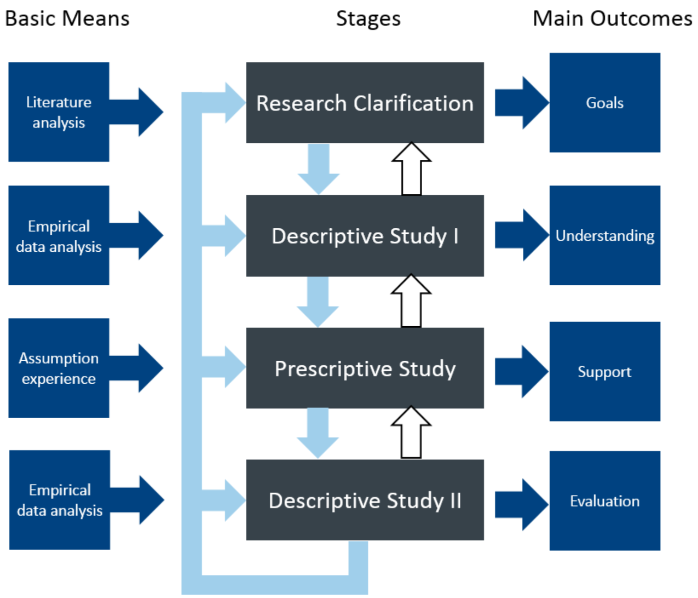

Figure 7. Design Research Methodology (Blessing, Chakrabarti 2009)

The research in this thesis is an interplay between theory and practice with utility and applicability as the main goals, meaning that both a theoretical base and a problem base is involved. The findings implemented in practice are analyzed by using empirical and observational studies. Further, implementations are assessed by performing quantitative assessments in order to evaluate the effects of implemented methods or best practices.

2.4. APPLIED METHODS

Both quantitative and qualitative methods have been used to address the research questions in this thesis. The methods applied in the six appended research papers cover the four research phases in the DRM, as shown in Figure 8.

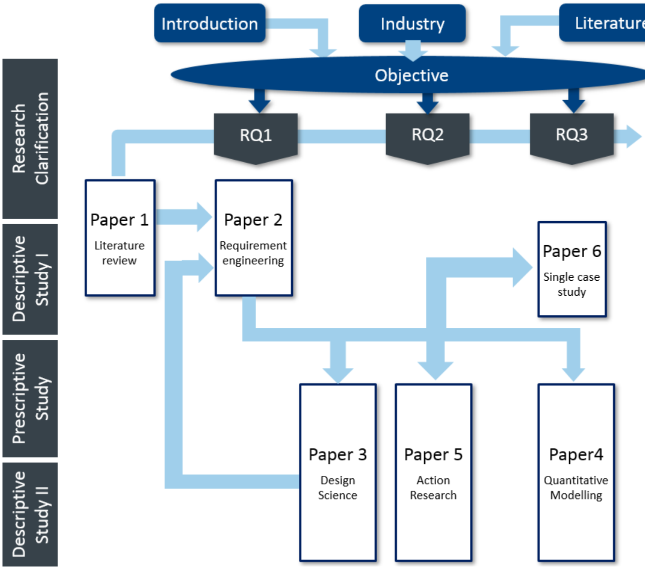

Figure 8. Overall research structure

The literature review in paper 1 contributes to all the research questions developed in the research clarification phase. The review does not directly answer the research questions, but rather supports their development and the general motivation regarding increased product variety, problems in industry and research gaps in literature. RQ1 is addressed by paper 2 and 3, RQ2 is addressed by paper 3 and 5, and RQ3 is addressed by paper 4 and 6.

In the descriptive study I phase, where the conceptual framework for stage configuration is developed, requirement engineering has primarily been used to conduct explorative studies on how stage configuration should be defined in the order capturing processes and aligned with stage-wise configuration modelling during new product development. Requirements are conditions or capabilities which must be met by the developed artifact and are often elicited from empirical data collections, such as interviews, observations, workshops, focus groups, etc. (Pandey, Suman et al.

2010). Requirement engineering is a systematic approach for gathering requirements from different sources of evidence and is often conducted in the early stages of development projects to guide activities towards achieving the requirements. Case studies are used in the descriptive study I phase in order to investigate how the production stage in stage configuration can benefit from implementing reconfigurability. For this purpose, case studies are generally considered as an appropriate method to conduct in-depth explorations of undeveloped research areas to fully understand complexity (Voss, Tsikriktsis et al. 2002). Case study is the study of a past or current phenomenon drawn from multiple sources of evidence, for instance interviews, observations and archives. Information on reconfigurability potentials is mainly gathered through interviews, workshops and factory visits with senior experts. Thus, applying case studies in the early stages of this research project contribute to the research objective by identifying vital variables and their relationships, as well as establishing reasons for the existence of the relationships.

In the prescriptive study phase and descriptive study II phase, artifacts are developed with the aim of developing processes, frameworks and tools to operationalize and support the execution of stage configuration. To do so, three distinct methods are used, namely design science from information research, action research, and quantitative modelling. Design science is used in the prescriptive phase to design a configuration ontology tailored to PLM systems and based on that suggest a stage-wise solution space modelling process aligned with stages in new product development and engineering design. Based on a case from Vestas, the modelling process is tested in the descriptive II phase. Design science is a research method centered around problem solving, aiming at extending the boundaries of knowledge and organizational capabilities by creating new artefacts (Peffers, Tuunanen et al. 2007). The development of artifacts must be grounded in practices, while the outcome of the process must add new knowledge to literature. Thus, design science typically uses existing knowledge from literature and apply it in practice to develop and build artifacts which have an effect in the organization (Hevner, March et al. 2004). Design science is further characterized by continues iterations between the practical environment and the design process, between the knowledge base and the design process, and between development and evaluation in the design process (Peffers, Tuunanen et al. 2007).

Furthermore, action research is used in paper 5 to propose a framework for modelling configurable product platforms supporting stage configuration and establish a classification on how to use different existing modelling methods. In the prescriptive phase, a modular, an integral and a mixed product architecture were assessed and modelled to clarify the relationships between product architectures, product platform modelling, and stage configuration. In the descriptive II phase, a classification framework is suggested. Action research resembles design science, but without the development and evaluation of an artifact. In action research, the main objective is to create changes in the organization by being deeply involved in the actions leading to changes (Karlsson 2010). In paper 5, action research was conducted as part of an existing project in the case company, by first collecting data on product architectures, secondly planning the modelling of the physical and functional part of the architectures, thirdly performing the modeling task and lastly evaluating it in relation to stage configuration.

Quantitative modelling was used in paper 4 to develop an optimization tool/model, concurrently optimizing product configuration and order allocation considering supply chain constraints. The prescriptive phase consisted of conceptual and scientific modelling, thereby establishing an integer linear programing (LP) model with the objective to maximize order profitability for the customers in the case company. In the descriptive II phase, the LP model was solved for 3 sales scenarios and 8 test cases defined from real sales situations in Vestas. Quantitative modelling is a mathematic description of a system using mathematical concepts and language, which is used to solve problems by means of calculations, statistics, simulations and other mathematical concepts (Karlsson 2010).

As the main objective of this thesis is to establish knowledge on stage configuration, an extended objective statement can be created incorporating the methodology, the methods, and the definition of knowledge:

“Develop the concept of stage configuration by using the design research methodology and mixed methods to obtain and analyze information to increase understandability and applicability on how stage configuration can support order capturing in the capital goods industry.”

CHAPTER 3. FINDINGS

Chapter 3 summarizes the six appended papers in the order which they were produced. Implications of research is added at the end of each summation to clarify how each paper contributes to answering the thesis' research questions. All papers can be found in appendix.

3.1. PAPER 1 - PRODUCT CONFIGURATION IN THE ETO AND CAPITAL GOODS INDUSTRY: A LITERATURE REVIEW AND CHALLENGES

The aim of the research presented in this paper is to answer the following two research questions:

- What are the main challenges in applying product configuration for complex engineered capital goods?
- Which solutions exist in research to address challenges in product configuration in the ETO and capital goods industry?

3.1.1. INTRODUCTION AND METHOD

Product configuration, ETO, and configuration of capital goods have separately been subject to multiple research reviews. However, these reviews are not conducted considering all three research domains collectively, which is the focus of this paper. The main focus areas in previous product configuration literature reviews are; configuring product platforms (Zhang 2015), general outlook on issues and future research in product configuration (Zhang 2014), reference frameworks for product configuration (Oddsson, Ladeby 2014) and product family modelling (Jiao, Simpson et al. 2007). Reviews on ETO supply chains focus mainly on supply chain management (Gosling, Naim 2009), while reviews on configuring capital goods focuses mostly on managing design variety (Veldman, Alblas 2012) and configuring capital goods with service systems (Roy, Shehab et al. 2009). In this paper, the literature review was conducted using a five-phased review approach inspired by Zin (2000). The approach consists of defining the search assignment, locating information resources, selecting search words, selecting search methods and evaluating the results. In this paper, all phases are conducted in three streams; first in a clarification stream (i.e. identifying challenges), second in a synthesis stream (i.e. finding solutions addressing the challenges), and third in an analysis stream (i.e. further analyzing solutions and methods identified). In total, 45 research publications were included in the revew.

3.1.2. CHALLENGES

By reviewing papers in the clarification stream, five main challenges were identified for applying product configuration in the capital goods industry: 1) Product characteristics are gradually determined over time, 2) long order horizons increase product demand mix uncertainties, 3) changes in product configurations cascade to downstream business processes due to their close integration, 4) high product complexity and comprehensive product variety, and 5) solutions outside the configurable solution space are required to large extent. These challenges are elaborated below.

Dynamic and unpredictable market conditions in the capital goods industry influence the customers' ability to commit product specifications, as the premise for making the decisions is likely to change multiple times before fully committing to the delivery. Customers therefore need to gradually specify products over time, while becoming more and more certain as the time to delivery shortens. Making stage-wise specifications is challenging in existing product configuration systems both in regard to solution space modelling and configuration. From a configuration point of view, current state-of-the-art configuration systems often only allow configuration of product variants and BoM generation if the entire product is specified. Performing stage configuration in today's configuration systems requires frequent alteration and reconfiguration to existing specifications, which can cascade changes to downstream supply processes. From a modelling point of view, product families are made available to customers through the configurator when they are fully developed. While dividing the commitment of product specifications in stages, product families must also be modelled in stages in the configuration system and step-wisely become available to customers. This is particularly present in tender-based order capturing, where submitting a bid can be a challenging task for customized products, as the design most often is incomplete or not aligned with the remaining attributes of the product platform.

Long order horizons have a significant influence on the need to specify products in stages. The long order horizon often leaves room for customers to change the product specification multiple times and thereby gain benefits from new opportunities or comply with new constraints either imposed/proposed by external factors or internal factors, such as frequent new product introductions. The challenges for the configuration system are to manage product and process knowledge for configured orders with due dates far ahead in the future, while improvements continually change both the product model and the supply setup for delivering the order. To manage these dynamics, companies often experience the need for a coherent integration between the product configuration system and supply chain processes. This close integration results from the fact that capital goods companies often manufacture products using a project management approach, rather than a production management approach. In this regard, the output of the configuration process is equal to a list of requirements for a project, where downstream activities and milestones need to planned according to the specific requirements. Not only does the configuration impact downstream supply processes, the processes also impact the configuration in form of procurement, master scheduling, forecasting, etc. Complex coordination between a myriad of internal stakeholders and management of product and process knowledge is also a challenge for capital goods companies, which can extensively prolong new product developments and quotations. Moreover, there appears to be a high product complexity and variety in the capital goods industry, which originates from unique operating environments rendering demand for optimizing each product variant to each individual customer. Thus, the challenge is to model knowledge for configurable product platforms at different maturity levels, consisting of a combination of different architectures with entangled physical and functional rules defining how valid product variants must be configured.

3.1.3. RESEARCH GAP

The review of challenges directs the review for corresponding solutions in the synthesis and analysis streams. Common for the identified solutions are five characteristics which they all to a certain degree represent: 1) stage-wise configuration and commitment of product specifications, 2) configuration flexibility to accommodate frequent requirement changes, 3) integration between the product configuration system and supply chain processes, 4) complex configuration knowledge and product structures are supported by the product configuration system and modelling processes, and 5) product engineering and development support product configuration of ETO orders.

By comparing the aforementioned challenges and the solutions, different research limitations are identified. First of all, high product complexity and variety, as well as ETO configuration are the two challenges most often addressed by solutions suggested in previous research. Furthermore, these two challenges are mainly researched in relation to each other and are to a certain degree included in multiple of the researched solutions. Challenges related to product characteristics being gradually determined over time during long order horizons and with a high integration between the configuration system and supply chain processes have on the other hand not been researched thoroughly. Moreover, these challenges are rarely researched in combination with each other. Long order horizons in product configuration have not been the main subject in any of the reviewed research papers and only to a limited extent in combination with gradually specifying product characteristics. Gradual product specification and configuration with supply integration are addressed to higher extent in previous research, however, rarely together or in combination with considerations of long order horizons. Thus, the literature review indicates a notable research gap in studying stage-wise specification in product configuration during long order horizons, while at the same time considering supply chain processes.

3.1.4. IMPLICATIONS

Paper 1 contributes to RQ1, RQ2 and RQ3 of this thesis by identifying a research gap between challenges and solutions for applying product configuration in the capital goods industry. RQ1 is motivated from the research gap on organizing stages in configuration to gradually determine product characteristic during long order horizons. RQ2 is motivated from the research gap on modelling complex product architectures to allow product characteristics to be specified gradually. RQ3 is motivated from the research gap on integrating product configuration and specification with supply chain activities. To summarize, the contribution of paper 1 is:

1) A consolidated overview of current challenges faced by companies in the capital goods industry when applying product configuration.
2) A consolidated overview of current approaches specifically applicable for companies in the capital goods industry for applying product configuration.
3) Identification of research gaps in terms of applying product configuration in the capital goods industry.

3.2. PAPER 2 - A CONCEPTUAL FRAMEWORK FOR STAGE CONFIGURATION

Following the findings from paper 1, the aim of paper 2 is to answer the following research question:

- How can product configuration decisions be divided into stages to increase the support of ETO and capital goods business processes, thereby enabling stage configuration?

3.2.1. INTRODUCTION AND METHOD

Based on the research gaps identified in paper 1 for gradually committing order specification during long order horizons while considering supply chain processes, the purpose of this paper is to develop the concept of stage configuration as a framework for allowing stage-wise postponement of configuration modelling and order specification decisions. To do so, a requirement engineering methodology proposed by Pandey et. al. (2010) was adapted and used in the industrial case company. In this research, subject matter experts were gathered in group discovery sessions to join face-to-face discussions on requirements for the concept of stage configuration. As a result, use cases were collected as requirements and input to constructing the conceptual framework. For instance, one identified use case is to perform a sales forecast and demand assessment. This use case is triggered by a date each month, which initiates the monthly Sales and Operational Planning process (S&OP). The actors involved are Sales Forecasters, S&OP Planners and Executive

Management. Preconditions are an enriched customer order with a high-level product specification, configuration costs and delivery specifications. Post conditions are inputs to the master planning process, and output is an approved demand forecast plan for the next 24 months. The use case possesses requirements towards the stage configuration concept's ability to enable a high-level product specification supporting the purpose of S&OP with the necessary product characteristics, cost, and delivery dates included. All use cases were collected as requirements and consolidated to construct the conceptual framework for stage configuration.

3.2.2. CONCEPTUAL FRAMEWORK FOR STAGE CONFIGURATION

The resulting conceptual framework for stage configuration defines and aligns stages in configuration modelling with stages in order specification. The stages in configuration modelling are further aligned with gates in the stage-gate approach for new product development. The order specification stages are positioned according to the stages in new product development and are thereby defined for when they can be executed at the earliest. Order specification stages are further offset with two stages compared to stages in configuration modelling, meaning that stage 1 in order specification can use information from stage 0 and 1 in configuration modelling etc. Each stage loops through a number of business processes until a "go" decision can be made on either the completeness of configuration modelling or the correctness of order specifications.

This paper proposes six stages in configuration modelling, simply named stage 0, 1, 2, 3, 4 and 5. The purpose of each stage is to model the consolidated outcome of the included business processes as they continuously iterate to mature new configuration knowledge. Stage 0 consists of market screening, product roadmap, and functional modelling. The outcome is a list of customer requirements linked to high-level product characteristics indicating how these requirements are intended to be addressed on a product family level. The product characteristics are mapped in a go-to-market plan, defining when product families should be available in different markets. Stage 1 includes product roadmap, functional modelling, and conceptual design. The outcome is a complete technical requirements specification list and a conceptual description of how the product architecture physically will address the list of requirements. Rules on how high-level product family characteristics can be combined are modelled in this stage. Stage 2 includes functional modelling, concept design, and embodiment design. The outcome is a detailed description of how product characteristics can be combined to create complete functional solutions. A preliminary generic BoM is established with a configurable product structure and configurable product modules. Stage 3 and 4 include concept design, embodiment design, and detailed design. In stage 3, the outcome is the modelling of how options and auxiliary solutions are constrained to a product family with the creation of configurable product modules. In stage 4, the outcome is a mapping between technical attributes and product characteristics and the establishment of components for module variants. Stage 5 consists of embodiment and detailed design. The outcome is finalized module variants with complete BoMs ready to be configured into a complete product variant. See Figure 9 for the complete conceptual framework.

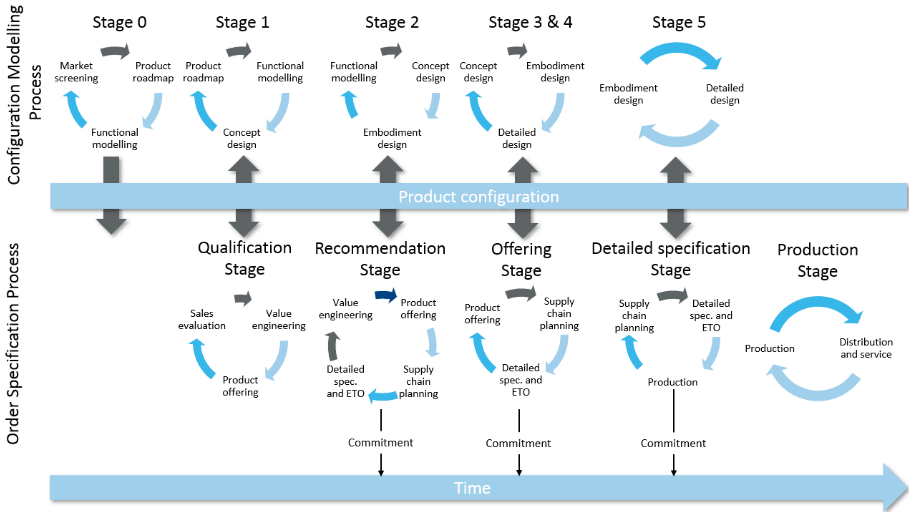

Figure 9. Conceptual framework for stage configuration

In order specification, 5 stages exist. The first stage is Qualification, the second stage is Recommendation, the third stage is Offering, the fourth stage is Detailed specification, and the fifth stage is Production. The qualification stage consists of sales evaluation, value engineering, and product offering. The outcome is a non-binding business case recommended to the customer based on the go-to-market plan and main product characteristics established in stage 0 and 1. However, the outcome is not yet mature enough to make a commitment of product specifications. The recommendation stage consists of value engineering, product offering, and supply chain planning. The outcome is a substantiated indicative offer with an optimized match between product configuration and operating environment. The optimization is based on information provided from stage 0, 1 and 2, which allows for an early commitment of high-level product specifications. The offering stage consists of product offering, supply chain planning, and engineer to order. The outcome is an unconditional signed customer order and a commitment of a more mature product specification including options with long lead times and high impact on capacity and costs. The detailed specification stage consists of supply chain planning, engineer to order, and production. The outcome is a final commitment of a complete product specification, with a completed design, before releasing the order to production. The production stage consists of manufacturing, distribution, and service. The outcome is an as-build configuration including suppliers and service providers.

3.2.3. IMPLICATIONS

Paper 2 contributes to RQ1 of this thesis by establishing configuration modelling and order specification stages and aligning these with stages in new product development. Each stage includes the participation of certain business processes and are aligned to define the concept of stage configuration aiming to postpone product configuration decisions. To summarize, the contribution of paper 2 is:

1) Configuration modelling can be organized into 6 stages during the stage-gate new product development process and includes requirement modelling, functional modelling, concept design, embodiment design, and detailed design.
2) Order specification can be organized into 5 stages: Qualification, Recommendation, Offering, Detailed design, and Production. Product specifications can be committed three times during the specification process, namely in the recommendation stage when an optimized indicative offer is provided, in the offering stage where an unconditional order is signed by the customer, and in the detailed specification stage just before the order is released for production.
3) The stages in configuration modelling and order specification are aligned in order for product configuration to commence as early as possible, however, also with the opportunity to postpone stages if needed.

By establishing and aligning configuration modelling and order specification stages, this proposed framework could potentially result in faster time to market, reduce risks of offering new products for tendering, and increase sales as an effect of being first-movers in the market. By committing partly specified orders, customers can postpone uncertain configuration decisions, thereby avoiding numerous changes to the order specification resulting in reconfigurations cascading in downstream supply chain processes.

3.3. PAPER 3 - PRODUCT CONFIGURATION MODELLING IN PLM ENVIRONMENT USING CONFIGURATION ONTOLOGIES

The aim of paper 3 is to answer the following two research questions:

- How can configuration ontologies be applied for solution space modelling in a product lifecycle management system?
- How can a coordinated process align solution space modelling with new product design in a product lifecycle management system?

3.3.1. INTRODUCTION AND METHOD

Making product families available to the marketplace is usually performed when the product is fully developed and designed, typically as an outcome from the idea-to-market development process (Jiao, Simpson et al. 2007). As described in paper 1, this norm is challenged in the capital goods industry, where first mover advantages, fast offerings, product customization, etc. are essential to stay competitive (Hicks, McGovern 2009). Thus, these conditions challenge the traditional process of formalizing product configuration knowledge, suggesting a stage-wise development of the solution space considering increasing design maturity levels. To gradually offer new product families, a close integration between product configuration, product development and engineering design processes must be established. As PLM is the systematic collection of activities for integrating and managing all product-related information and processes throughout the entire lifecycle from initial idea to disposal (Stark 2015), PLM is suggested as system for managing this integration. In this regard, configuration ontologies have in previous research improved transparency in configuration modelling and design knowledge for complex products when implementing incremental changes to the knowledge base (Yang, Dong et al. 2008, Xuanyuan, Li et al. 2016), but are rather scarcely investigated in relation to PLM systems.

Therefore, to develop the beforementioned process integrations supported by a PLM configuration ontology, this paper uses design science as research method. Both the configuration modelling process and the ontology is developed from a case in the industrial case company and investigated before and after implementation. Before implementation, configuration engineers formulated six main challenges in regard to configuration modelling in the PLM system: 1) unstructured approach for modelling the solution space, 2) lack of overview due to increased complexity, 3) difficulty in doing diagnosis, 4) time consuming syntax, 5) complications and comprehensiveness in making all the configuration constraints, and 6) difficulty in matching knowledge acquired from domain experts. Hereafter, a configuration ontology was proposed.

3.3.2. PLM CONFIGURATION ONTOLOGY

A configuration ontology can be described as an explicit formal specification of a shared conceptualization consisting of concepts, classes, and relations, and describe what must exist in a context of entities for the entire system to be true (Soininen, Tiihonen et al. 1998b). The proposed ontology is based on the product variant master (PVM) concept (Hvam, Mortensen et al. 2008) and therefore consists of a part-of and a kind-of structure, both represented as a context class in the ontology. The context class is used for containing information on settings and governance-procedures uniquely to a specific product platform, shareable with other contexts as well. The part-of-structure includes a taxonomy of the physical product platform composing the entire structure of sub-assemblies, modules, and components. The part-of-structure must be further enriched with additional information, such as cardinality of modules, mandatory vs. optional modules, quantities, lifecycle state, etc. The kind-of-structure defines how a class can appear in several variants with different combinations of values, lifecycles and availabilities. The main part of the kind-of-structure is the definition of characteristic values and how they can be combined to create valid product specifications. All characteristics and values are maintained in a characteristic pool where sets of the characteristic pool can be created and assigned to a different context for configuration purposes. Constraints determine valid combinations of values and can as well as values be governed for availability. The availability class defines a date range for when a value can be selected, or a constraint is valid. Values are assigned to either components, modules or sub-assemblies in the part-off-structure, to enable the configuration of the physical product. Lifecycle statuses can be applied to a vast range of classes, namely all classes in the part-of-structure, values, set of characteristics, and to individual characteristics. The lifecycle status controls the maturity of the solution space and thereby when each solution can be sold and delivered.

3.3.3. PROCESS FOR SOLUTION SPACE MODELLING IN PLM

The process for solution space modelling in PLM corresponds to the configuration modelling part of the conceptual framework for stage configuration developed in paper 2 and is further advanced based on the PLM configuration ontology developed in the previous section. The process guides knowledge representation activities and align these with generic stages in engineering design and gates for stage-gate new product development. The modelling process is aligned with gate 1, 2, and 3 in new product development and 5 stages in engineering design namely, requirements modelling, functional modelling, concept design, embodiment design and detail design. The modelling process consists of 6 stages, each including certain modelling activities based on certain design activities, see Figure 10.

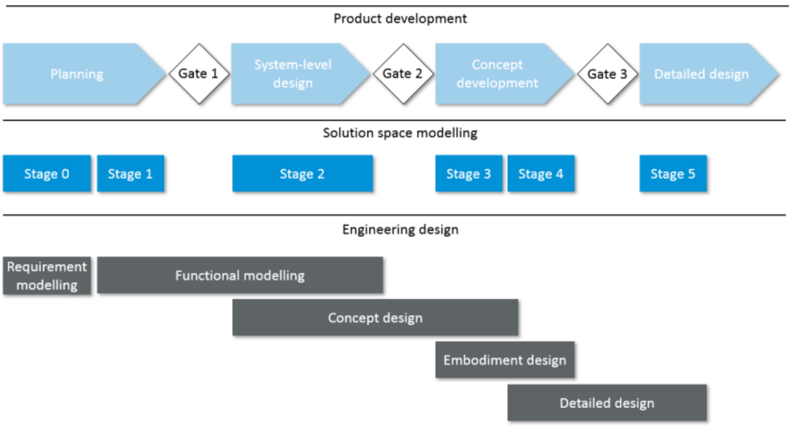

Figure 10. Solution space modelling aligned with new product development

Stage 0 completes requirement modelling and includes screening of the market for new sales opportunities and formalizing the requirements as either market or customer requirements. The requirements can hereafter be related to product specifications, costs, transport, safety, recycling, etc. Requirements are modelled together with markets, thereby defining the degree to which the requirements will be fulfilled, in the corresponding markets, and when they are expected to be satisfied by the new product family. Stage 1 concludes stage 1 in new product development and includes the transformation of market and customer requirements into a complete technical requirements specification list. Based on the requirements list, a high-level conceptual design describing the physical architecture is established and scoped for when certain solutions can be made available to which markets. To represent this, constraints between high-level product characteristics and market requirements are modelled in the configuration system. Stage 2 completes functional modelling and stage 2 of new product development. This stage includes constraining combination of product characteristics to create complete functional solutions and a high-level generic BoM structure resulting from concept design activities. The functional solution and the high-level GBoM are implemented into the configuration system. Stage 3 completes concept design by further defining the architecture for auxiliary and optional systems and evaluating the main functional variants defined in stage 2 against markets and customer requirements. Configurable sub-systems and customer unique solutions are further developed and implemented in the configuration system. Stage 4 completes embodiment design and stage 3 in new product development. This stage includes a detailed layout of designs and interfaces resulting in a full list of 2D and 3D documentations. Based on this, instances of product modules are created with an availability range. Depending on the design maturity in stage 4, the detailed product structure can either be represented through product characteristics relevant to sales (customer view) or by technical attributes assigned to product modules and linked to sales product characteristics (engineering view). Stage 5 conclude the detailed design, by creating the BoMs for all module instances, which enables the configuration of complete product variants.

3.3.4. IMPLICATIONS

Paper 3 contributes to RQ1 and RQ2 of this thesis by first developing a configuration ontology for PLM and then using the ontology to develop a stage-wise modelling process in a PLM system, aligning solution space modelling with engineering design and new product development. From the combined configuration ontology and modelling process, an increased understanding of constructs in PLM configuration is achieved with a gradual configuration of product families having multiple maturity levels, thereby improving the transparency between the physical and functional product platform structures. To summarize, the contribution of paper 3 is:

1) Definition of six solution space modelling stages in PLM and alignment of these with requirement modelling, functional modelling, concept design, embodiment design, and detailed design during stage 1, 2, 3 and 4 of new product

development, thereby extending research on applying knowledge representation for configuration systems in PLM environments.

2) Extension of the use of configuration ontologies towards PLM systems based on a product variant master approach, defining relations, classes, and concepts in the physical and functional part of the product structure. New knowledge is thereby created for existing configuration ontologies through a complex empirical case example.
3) Demonstrating that product families can be modelled in a stage-wise approach and offered through a PLM system. First, on a high functional level in the early phases of new product development, secondly on a detailed functional level with a high-level product architecture defined in concept and embodiment design, and thirdly on a detailed physical level with complete BoMs finished through embodiment and detailed design activities.

Modelling configurable product families in product lifecycle management systems enables a closer integration between product development and sales, thereby reducing the lead time for offering customizable products, while reducing internal complexity. The stage-wise modelling approach further supports shareability and transparency of the product family model by improving analytic, diagnostic, and reporting capabilities throughout the modelling and release processes.

3.4. PAPER 4 - CONCURRENTLY OPTIMIZING PRODUCT CONFIGURATION AND ORDER ALLOCATION FOR CAPITAL GOODS CONSIDERING SUPPLY CHAIN CONSTRAINTS

The aim of paper 4 is to answer the following two research questions:

- How can conceptual modelling and linear programming be applied to model available-to-promise and product configuration supporting optimal product selection?
- How does a combined configuration and optimization approach impact order profitability?

Specifically, the research presented in this paper addresses the recommendation stage defined in paper 2.

3.4.1. INTRODUCTION AND METHOD

The capital goods industry is increasingly adapting tendering as the main form of acquiring sales contracts, often exclusively competing on maximizing ROI for the customer by reducing costs and improving product performance (Wu, Kleindorfer et al. 2002). Reducing the cost is based on the total cost of ownership (TCO) ranging from initial investment to service and disposal costs (Ferrin, Plank 2002). Product performance is measured in terms of generated income and is based on how well the purchased product operates in its intended operating environment. Thus, the objective for companies engaging in tendering processes is to optimize ROI for the customer, by not only configuring the best performing product, but also the lowest TCO, which requires a close integration with supply planning and order fulfillment processes.

Planning and fulfillment processes has been subject to optimization studies in previous research (Christou, Ponis 2009, Zhao, Ball et al. 2005), however, rarely in relation to optimizing product selection. Other studies have proposed a concurrent optimization approach between product configuration and production planning (Lamothe, Hadj-Hamou et al. 2006, Aldanondo, Vareilles 2008, Pitiot, Aldanondo et al. 2013, Wang, Zhong et al. 2017). However, these studies do not consider demand allocation in a global supply network in combination with optimal product selection. Thus, the aim of this paper is to develop a quantitative model that optimizes the profit for the customer, by concurrently selecting a combination of products and planning the supply. To reach this objective, this paper applies the framework proposed by Bertrand and Fransoo (2002) on modelling and simulation research. The conducted research is empirical prescriptive as it first conceptualizes the case problem into a model defining the objectives, model responses, experimental factors, level of detail, and assumptions (Robinson 2008). Secondly, it builds a scientific model based on the conceptual model. Thirdly, the scientific model is solved in accordance with a test protocol and lastly analyzed for implications in the industrial case company.

3.4.2. CONCEPTUAL AND SCIENTIFIC MODELLING

The objective of the optimization model is to maximize the customer profit by 1) determine the amount and combination of ordered products, and 2) determine the allocation of production and demand for the ordered products. The outputs/responses of the model are used to assess the objectives and must therefore be profit, quantity of ordered products, and planning of demand and production allocation. The responses can be influenced by changing the experimental factors. Experimental factors are inputs provided by the customer and may be subject to changes. The experimental factors are: operating conditions, delivery timing, operating lifetime, maximum investment costs, maximum installed capacity, maximum number of installed products, local content, exclusion of plants, and exclusion of products. The level of detail can be categorized into order, supply, application environment and solution space. The details of the order category include the products being ordered, the quantity, delivery timing, profits, and local content requirements. The details for the supply category include manufacturing and demand plans for each plant, manufacturing capacities, make to order lead times, and the manufacturing footprint. The details for the application environment include operating conditions and a power purchasing agreement (PPA) defining the income per produced megawatts (€/MWh). The details for the solution space include a collection of product configurations and their rated performances.

The conceptualization process is concluded with a conceptual model used to build the scientific model. The scientific model is programmed as an integer linear programming problem with the objective function shown in Equation 1.

Equation 1. Objective function: Maximizing profit for the customer

$$Max \sum_{\omega=1}^{\Omega} (AEP_{\omega} * I * q_{\omega} * OT)$$
$$- \sum_{\omega=1}^{\Omega} \sum_{f=1}^{F} \left(CO_{\omega f} * q_{\omega f}\right) + \left((SF_{\omega} * q_{\omega}) * OT\right) + (SV_{\omega} * AEP_{\omega})$$

The objective is to maximize the profit by maximizing the income generated by the selected products while minimizing the cost of ownership. Variables and decision variables for the objective function are listed in Table 2.

Table 2. Variables and decision variables for maximizing profit for the customer

Parameters	**Description**	**Dimensions**	**Source**
ω Ω	Type of product *ω* variant: ω = 1... Ω	Product	Products in scope for the model
f F	Plant *f*: f=1… F	Plant	If a Plant can produce one of the candidate products it is in the scope of the model.
Variables	**Description**	**Dimensions**	**Source**
AEP_{ω}	Annual Energy Production generated for product *ω* at site	MWh/product	Calculated variable based on candidate products and site condition
OT	Operating time *OT* for site	years	Expected operating and lifecycle time is determined by the customer
I	Income *I* Income for power produced	€/MWh	The PPA. Denote what the produced wind power can be sold for and is provided by the customer
$CO_{\omega,f}$	Customer cost of suppling product *ω* form plant *f*	€/unit/product	CAPEX for the customer, provided by Sales and Finance
SF_{ω}	Annual fixed service costs for *ω* product	€/unit/product	Each product has a fixed annual service cost and is provided by the service department
SV_{ω}	Variable service cost for producing one MWh from product *ω*	€/MWh	Service cost is provided by service sales
$q_{\omega,f}$	Ordered quantity for product *ω* in Plant *f*	unit/product/plant	Integer decision variable

Customer and available-to-promise (ATP) constraints are further added to the model in accordance with the conceptual model.

3.4.3. PRODUCT SELECTION OPTIMIZATION

The optimization model is enriched with information on manufacturing costs, production plans, demand plans, lead times, manufacturing footprint, etc. and is executed according to a test protocol. The test protocol consists of three sales scenarios: 1) maximum installed megawatt, 2) maximum number of products, and 3) maximum investment cost. For each sales scenario, eight test cases are conducted in accordance with order capturing situations in the industrial case company. By selecting eight test cases, the optimization model is further tested for its general applicability in the case company. The test cases are: 1) no additional constraints, 2) local content, 3) changing site conditions, 4) delivery schedule, 5) one product configuration for the entire site, 6) one supplier, 7) one supplier and one product configuration for the entire site, and 8) a combination of constraint 2, 4 and 5. The results of the optimization are depicted for sales scenario 1 in Figure 11. The results of sales scenario 2 and 3 can be seen in the appended paper 4.

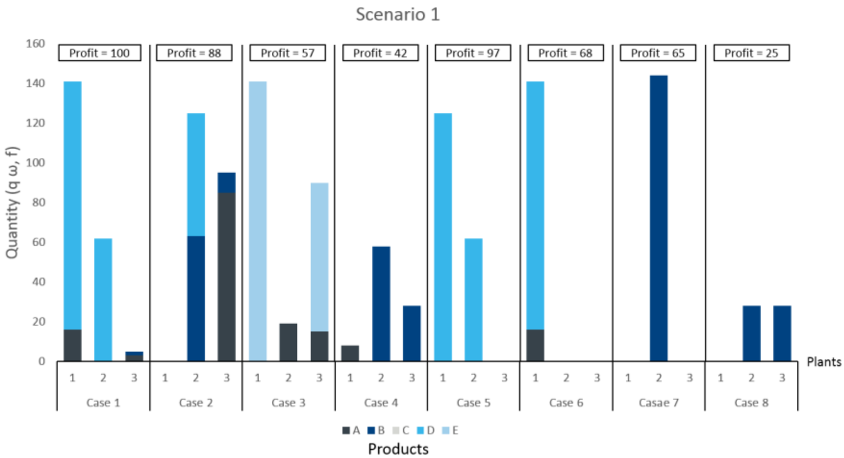

Figure 11. Optimized configurations and planning results for sales scenario 1

Five products with different maturity levels and design specifications were subject to the optimization. New products have higher performance in regular application conditions, lower operating expenses, but higher investment cost and longer lead times. More mature products have a lower performance, lower investment costs, shorter lead time, but higher operating expenses. The maturity of products is also reflected in the manufacturing footprint as new products are often produced on a restricted number of plants, while older products have been implemented on multiple plants. Considering both product specifications and the supply setup, the output from the three scenarios and test cases are rather different. The results show that new products are usually favored in scenario 1 due to the superior performance, however, in cases with local content or strict delivery schedules, the long lead time is often a disqualifier. Mature products are typically selected in scenario 2, mainly because the short lead time allows for a more flexible allocation of production with greater exploitation of increasing the supply volume (gearing). In scenario 3, mature products are nearly exclusively selected in all test cases. New products in scenarios 3 have too high investment costs and become too expensive for a reduced operating lifetime. This causes the selection of more mature products with lower investment costs and a more diverse manufacturing footprint.

The most severe impact on profitability is an uncertain and frequently changing definition of the application environment, which can cause a selection of products not designed for its application. A challenging delivery schedule can in some cases implode the profitability. Lastly, a combination of multiple constraints included in the quote for tender have a tremendous negative effect on the business case, as shown in test case 8.

3.4.4. IMPLICATIONS

The optimization model presented in this paper aims at enabling the commitment of high-level product specifications in the recommendation stage considering the stage configuration concept, thereby contributing to RQ3 of this thesis. The commitments are achieved by optimizing the profit for a customer's business case by integrating product configuration, ATP, and application environment in one optimization model. By doing so, supply chain planning changes from being reactive in the late stages of order capturing to be proactive in the early stages. Response times for business case creation can potentially be reduced, due to a decrease in iterations for order capturing and an early alignment on expectations between supply and customer demands. The optimization model maximizes profitability for a selection of product specifications by taking the entire product portfolio into consideration with the corresponding manufacturing footprint, costs, and lead times. To summarize, the contribution of this paper is:

1) An integer linear programming model which optimizes the selection of products by maximizing order profitability in the order capturing process given a specific application environment.
2) Integration of ATP and product specification, thereby concurrently configuring the product, delivery times, and demand/production allocation in a global manufacturing network.
3) Insights from case results showing significant diversity in product specification and demand allocation, based on applied supply constraints and customer requirements.

3.5. PAPER 5 - MODELLING CONFIGURABLE PRODUCT PLATFORMS: AN EMPIRICAL STUDY IN THE CAPITAL GOOD INDUSTRY

The aim of paper 5 is to establish a classification on how the modelling of configurable product platforms can support stage configuration.

3.5.1. INTRODUCTION AND METHOD

In the capital goods industry, product specifications need to be conducted in stages due to volatile, uncertain, and unpredictable market conditions, and is dependent on the certainty of factors determining the configuration (Bennett, Lemoine 2014, Veldman, Alblas 2012). This causes customers to postpone configuration as much as possible. However, in current product configuration systems, it is typically not possible to postpone configuration decisions in a stage-wise manner, which forces customers to submit highly uncertain configurations, causing changes of these multiple times before a complete order can be fully committed (Oddsson, Ladeby 2014, Zhang 2014). This further causes challenges in the supply chain, as multiple processes e.g. costing, manufacturing preparation, planning, and forecasting act on uncertain BoMs subject to multiple changes. Therefore, this paper explores how current configuration modelling methods can enable the configuration of partially specified products, consisting of a clear specification of configured and non-configured BoM components. This exploration was enabled in the industrial case company and required hands-on involvement from both researchers and practitioners. The paper therefore follows the action research cycle proposed by Coghlan (2019). The action research cycle is first used to assess and select an integral, a modular, and a mixed product architecture from the case company. Secondly, it is used for applying different modelling methods to the different product architectures, and thirdly for evaluating the relationships between product architectures, product platform modelling, and stage configuration.

3.5.2. PRODUCT PLATFORM MODELLING AND STAGE CONFIGURATION

Modelling product platforms for configuration generally consists of defining rules for how characteristic values can be combined in a valid way, mapping these values to physical components, and the physical structure expressed through the GBoM. The result is a physical and functional structure from which all product variants can be configured. As an example, Figure 12 shows a conceptualized GBoM being configured three times during a product specification process and committed in a stage-wise approach in the recommendation, offering, and detailed specification stages, defined in the stage configuration concept proposed in paper 2.

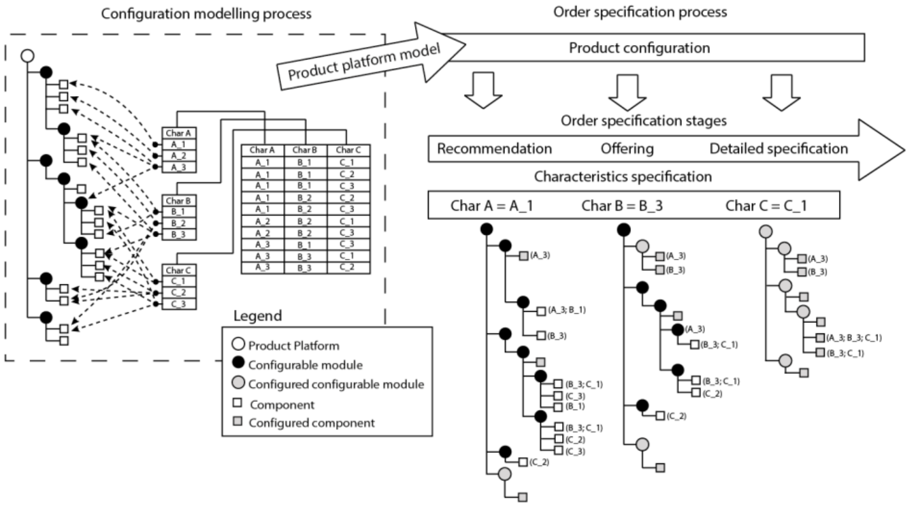

Figure 12. Conceptual example of stage-wise configuring a product platform

The left-hand side of Figure 12 shows the configurable product platform with a GBoM as physical representation and a decision table as functional representation. The right-hand side of Figure 12 shows partially specified BoMs as output in each configuration stage. The completeness of the configured BoMs is maturing as the configuration process progresses and evolves based on configuration decisions made in current and previous stages.

3.5.3. MODELLING CONFIGURABLE PRODUCT PLATFORMS

Modelling configurable product platforms to support stage configuration aims at specifying as many components as possible from as few selections of characteristic values as possible. Due to the low reuse of components, integral product architectures can avoid redundant mappings between characteristic values and physical components, by representing the architecture on a product level with characteristic control IDs. The GBoM thereby consists of end-products represented with distinct module variants with predefined BoMs. Characteristic values are constrained toward a control ID and can be combined in various ways, as long as the characteristic values are constrained to the same control ID. Using control IDs to group valid combinations of values allows for fewer specifications of characteristics, due to reuse of functional solutions across physical ones. Integral architectures further endure large differences between constrained and unconstrained functional solutions, which make decision tables and conditional statements using control IDs suitable for reducing configuration rules, and thereby simplify the knowledge base.

Modular architectures have a higher reuse of components and usually support stage configuration more than integral architectures, especially if the architecture can be modelled on a component level instead of the more commonly applied module level. A module variant in a modular architecture often has one characteristic value mapped to it, meaning it is independent from how the rest of the product is configured. In these cases, module variants often share standard components, but as values are mapped on a module level the standard components are not included in the configuration until the specific value is specified. The same applies in cases where multiple values are mapped to a module but is only relevant for part of its components. Thus, in modular architectures the GBoM should be modelled on a component level to avoid making components dependent on values they are independent from. Moreover, the configurable module structure should avoid value dependent intermediate configurable levels, in order to reduce cascading value dependencies to lower BoM levels. Conditional statements and arithmetic constraints are the preferred methods to represent configuration rules respectively for add-on options, independent functions, and parametric inequalities.

Mixed architectures should be configured on a module level for integral parts and on a component level for modular parts. Modelling on a product level creates redundant BoMs due to commonality. Unconstrained add-ons in the modular part of the architecture should be modelled using conditional statements, while specific combinations of values in the integral part should be modelled using decision tables.

The learnings from modelling the three different architectures are aggregated in a general framework for modelling configurable product platforms, aiming at supporting stage configuration by specifying as many components as possible, based on as few specified product characteristics as possible. The framework consists of three dimensions, namely functional, physical, and mapping independencies ranging from very low to very high on a 5-point Likert scale. The modelling methods applied to the three architectures are positioned in the framework along the three dimensions suggesting how they should be applied dependent on the modularity of the architecture. For highly integral architectures, the physical dimension should be on a product level, the functional dimension should use decision tables or control IDs, and the mapping dimension is a one-to-many relation between components and values. For the modular architecture, the physical dimension is mostly on a component level, the functional dimension uses conditional statements, and the mapping dimension is one-to-one. For the mixed architecture, the physical dimension is typically modelled on a module level while the functional dimension ranges between decision tables, control IDs, and conditional statements.

3.5.4. IMPLICATIONS

Paper 5 contributes to RQ2 of this thesis by establishing a classification on how to model configurable product platforms supporting stage configuration and by providing empirical insights into the relationships between product architectures, product platform modelling, and stage configuration. The configuration modelling approaches can be elicited from the proposed classification framework in any product configuration modelling scenario, by 1) scoping the platform subject to modelling, 2) examining the physical, functional and mapping independencies of the platform, and 3) positioning the result of the examination in the classification framework and inducing the suggested modelling methods. To summarize, the contribution of this paper is:

1) Explorative insights from modelling configurable product platforms for stage configuration.
2) Established connections between product architectures, product platform modelling and stage configuration.
3) Modelling classification to simplify product platform modelling and configure as many components as possible from as few value selections as possible.

By using the modelling framework and the provided classifications in the order specification process, downstream supply chain processes can provide high quality responses in regard to forecasting, quotation, and planning for partly configured products and required product not yet fully developed. Instead of needing a fully specified functional and physical structure of the ordered product, supply chain processes can employ estimation methods with transparent uncertainties as responses to customers, thereby significantly reducing the time for quotation and improving quality.

3.6. PAPER 6 - RECONFIGURABLE MANUFACTURING: A CASE-STUDY OF RECONFIGURABILITY POTENTIALS IN THE MANUFACTURING OF CAPITAL GOODS

The aim of this paper is to answer the following research question:

- What are the potentials for reconfigurability on multiple production levels and their relationship towards reconfigurability drivers and purposes?

3.6.1. INTRODUCTION AND METHOD

In the capital goods industry, customers need to configure product specifications in stages due to uncertain, volatile and unpredictable market conditions, forcing them to postpone configuration decisions as late as possible. Continuously changing product specifications and late order commitments require a changeable manufacturing setup, capable of reconfiguring its ability to produce different product variants at different volumes and different times, and to efficiently introduce new products into production (Tracht, Hogreve 2012). These abilities must be present on all production levels, including supply network, factory, section, system, cell, and workstation level (ElMaraghy, Wiendahl 2009). In this regard, reconfigurability is a system’s ability to change its structure and resources rapidly and cost-efficiently, in order to possess exactly the capacity and functionality needed, exactly when needed (Koren, Gu et al. 2017). To investigate reconfigurability potentials in the capital good industry, this research was conducted as a case study consisting of semi structured interviews with central employees with 60 minutes duration each. Some of the interviews were further combined with factory visits and half day workshops. Extensive field notes were taken during the interviews and factory visits and afterwards coded and categorized in “change drivers” and “potentials”.

3.6.2. RECONFIGURABILITY DRIVERS AND POTENTIALS

Through the case study, 27 drivers of reconfigurability were discovered and consolidated into 5 main categories. The categories are: 1) local content and sub-contracting requirements, 2) high competition on customer ROI, 3) frequent introduction of new products, 4) uncertain and diverse demand, and 5) requirements for non-offered products. The potentials for reconfigurability are mapped with drivers, changeability objectives and production levels. The potentials are summarized below and linked to each driver.

1) On the network, factory and system level, reconfigurability potentials are mostly characterized by mobility, in order to meet changing local regulations and requirements for subcontracting. Thus, mobility as a characteristic of reconfigurability enables diversifying the design of manufacturing setups and manufacturing closer to the customer (e.g. a factory-in-a-box concept), thereby reducing transport cost significantly.
2) Reconfigurability in terms of mobility and integrability has the potential to enable production of a more diverse range of variants at each factory, rather than operating dedicated factory setups. Further, this allows for planning production at the most cost-efficient manufacturing sites compared to the demand and specific projects i.e. installation location. Eventually, this will allow for higher competitiveness for each order.
3) Reconfigurability allows for more efficient introduction of new products in the capital goods case. With extraordinary requirements for space and weight of components, modular, scalable, and convertible buildings, equipment, tools, etc. will enable easier conversion to new products, including testing of these at each installation sites.
4) Significant diversity and fluctuations of demand is a key driver of reconfigurability potentials on various levels. On network level, the ability to deliver capacity on demand independently of products being sold is a key potential, whereas on factory and section level, cost reduction can be enabled by modular transportation and manufacturing equipment for large diverse components. Lastly, mobility of equipment enables rearrangement of workstations and easier line balancing when changing between different variants in factories.

5) Reconfigurability allows for more efficient adaption to requirements of products outside the existing solution space, especially in combination with additive manufacturing techniques such as 3-D printing. Building additive manufacturing equipment with a modular architecture can further increase the level of supply responsiveness.

3.6.3. IMPLICATIONS

Paper 6 contributes to RQ3 of this thesis by establishing an empirical overview of reconfigurability potentials in the capital goods industry considering multiple supply levels and changeability purposes. Supply levels are at network, factory, system, section, cell, and work station level. Changeability purposes relate to manufacturing different variants, scaling capacity, and new product introduction. Reconfigurability is concluded to be necessary on all supply levels to fully support order capturing in the capital goods industry. Reconfigurability can support order capturing when bidding for new orders in the recommendation and order stages, by enabling the supply from multiple manufacturing sites and thereby reducing supply costs while complying with capability, capacity, and lead time constraints. To summarize, the contribution of this paper is:

1) An overview of how reconfigurability can potentially support changeability drivers for increasing return of investment for customers with uncertain diverse demand and local requirements.
2) Reconfigurability potentials are mostly present on network, factory, and system level, focusing on creating a flexible manufacturing footprint to increase cost efficiency as a source of competitiveness.
3) There are significant potentials in localizing supply through implementing reconfigurability across supply levels, thereby decentralizing manufacturing with reduced lead time and costs.

Reconfigurability can potentially increase cost competitiveness in companies. This is enabled by configuring a flexible manufacturing footprint allowing orders to be produced at the most cost-efficient factory. This further adds flexibility for optimizing order profitability for the customer, as fewer constraints are restricting where the order can be delivered from. Scalable capacities can additionally reduce costs and lead time by quickly changing the supply system’s structure and capabilities.

CHAPTER 4. CONCLUSION

The objective of this PhD thesis was to develop the concept of stage configuration and establish knowledge on how this approach can support order capturing in the capital goods industry. Both the concept of stage configuration and the knowledge generated for how it can support order capturing was created in an industrial setting to ensure practical relevance and applicability. To ensure both practical relevance and advancements in state-of-the-art on product configuration systems, this research applied design research methodology to 1) descriptively define current state, 2) prescriptively suggest how to advance, and 3) descriptively establish knowledge of how the suggested tools and methods impact practice and theory. The research objective of the thesis was addressed by answering three research questions, which are summarized in the following in terms of the contribution of this thesis.

4.1. RESEARCH CONTRIBUTIONS

RQ1: How can product configuration be organized in stages to support engineering and supply processes, thereby enabling stage configuration?

Paper 2 and 3 answer RQ1. This research proposes to organize product configuration into two main processes, namely solution space modelling and product specification. The solution space modelling process should consist of 6 configuration stages and be aligned with gates in new product development and engineering design. The solution space includes a physical and functional architecture, which must be gradually modelled in each configuration stage. In the early stages of solution space modelling, the functional architecture is represented on a high-level with a corresponding go-to-market plan and is based on market screening, product roadmap, functional, and concept design. In the mid configuration stages, the solution space is maturing with a detailed functional architecture, a high-level physical product structure, and is based on functional, concept, and embodiment design. In the late modelling stages, both the functional and the physical architecture are fully defined, including complete BoMs and are based on embodiment and detailed design activities. Due to the close integration with new product development and engineering design, the solution space modelling stages are conducted in a PLM system supported by a PLM specific ontology.

The product specification process is proposed to consist of five stages. In the early specification stages, qualification and recommendation aim to configure the optimal configuration for the customer and present a profitable indicative business case with high-level commitment of product characteristics. The early stages are based on sales evaluation, product offering, value engineering, and supply chain planning. In the mid stage, offering aims to commit a more detailed product specification mature enough to firm unconditional customer orders. In the late stages, the detailed specification and production aim to complete the product specification before releasing a production order. The unspecified product characteristics are specified and the sales order is made ready to be manufactured. The late stages are based on supply chain planning, detailed specifications and engineer to order, production, distribution, and service.

RQ2: How can modelling of configurable product platforms support product configuration in stages?

Paper 3 and 5 answer RQ2. Often in today's capital goods industry, downstream supply processes mainly act on information from the configured physical architecture in the form of components with corresponding designs. The common way to configure components is to specify product characteristics, which are mapped to the physical structure of the product platform, thereby selecting which components to include in the configured product variant. The objective of modelling configurable product platforms for stage configuration is therefore to generate as many components as possible, with as few specifications of product characteristics as possible. To do so, this research suggests a classification framework to support selection of configuration modelling methods for stage configuration dependent on whether the product platform architecture is integral, modular, or a combination of the two. The framework further consists of three dimensions, namely the physical product platform structure, the functional product characteristic structure, and the mapping between the two. If the architecture is integral, the physical structure is modelled on a product level and the functional structure mainly uses decision tables and control IDs in conditional statements, and the mappings are one-to-many. If the architecture is modular, the physical structure is mainly modelled on a component level and the functional structure uses conditional statements, and mapping is one-to-one. If he architecture is a combination of integral and modular, the method used in each dimension is also a combination, however, the physical structure is mainly modelled on a product module level and the functional structure is a mixture of decision tables and conditional statements.

RQ3: How can configuration be applied to optimize order profitability considering supply chain constraints?

Paper 4 and 6 answer RQ3. This research proposes an optimization model using integer linear programming to optimize order profitability for the customer in the order capturing process. The model considers product configurations, the supply chain setup, and the application environment. Product configurations are further included with performances, while the supply chain setup is included with costs, manufacturing footprint, lead time, capacity, demand and production plans. The application environment is included with variables describing operating conditions. Based on this information, the model responds with an optimal specification of product configurations, results on where the configurations should be produced, when they should be produced, and quantities to be produced in each factory. The model is further tested in three sales scenarios with eight test cases in the industrial case company to evaluate practical applicability. The tests show that varying customer demands, supply chain constraints, and operating conditions greatly impact optimized product specification. Both customer, supply and application constraints must be considered simultaneously to ensure optimized product selection.

A further optimization of product selections and thereby order profitability can be achieved by reducing supply constraints. The supply constraints can be reduced by employing a reconfigurable manufacturing system (RMS). RMS has the ability to change the supply structure and resources rapidly and cost-efficiently, in order to possess exactly the capacity and functionality needed, exactly when needed. In this regard, the manufacturing footprint would be widened, capacities would be scalable, lead times more flexible and local content enabled to higher extent.

4.2. GENERALIZABILITY AND INDUSTRIAL IMPLICATIONS

4.2.1. GENERALIZABILITY

The presented framework for stage configuration is proposed in respect to capital goods companies with long order horizons and a need to both develop and specify products in stages. However, some durable consumer goods such as cars, home appliances, furniture, etc., with roughly the same characteristics as capital goods can also benefit from the framework. The solution space modelling part of the framework can be used for all companies engaging in stage-gate product development, while the order specification part is more company specific dependent on the need to qualify, engineer, and recommend product solutions both before, during, and after an order is committed. The alignment of stages is mostly applicable for companies that need to communicate and offer products quickly during new product development in close integration with supply chain processes, such as in make-to-order and engineer-to-order scenarios. The solution space modelling part was performed in a widely used PLM system, which votes well for its application in other PLM systems using the same approaches. Thus, it is expected that applying the modeling approach and framework to some degree in other cases is feasible, but relatively simple and fast-moving consumables such as food, cosmetics, cleaning product, etc., are not expected to experience major benefits.

Modelling product platform architectures to support stage configuration is proposed through a classification framework and is assessed as having widespread application in industries, since all products have architectures and multiple companies often model those architectures for configuration to configuring product variants. The framework is iteratively created based on modelling product family models in an industrial case company. Modelling other product families in other companies can give other conclusions dependent on the amount of variety, the relationship between functional and physical solution, and commonality between variants. These measures can however be different within the same product architecture, which stresses the importance of explicitly clarifying the assessment of the architectures. The framework is generalizable across companies using product configuration, especially stage configuration, but can endure minor alterations dependent on the specific architecture being configured.

The developed optimization model is rather case specific, however, with some elements of generalizability. The integration between product configuration and the supply chain setup, modelled in the optimization model, can generally be applied in all industries where customers can formulate a quantifiable objective for maximizing return of investment. Further, the model would presumably work for companies with multiple factories in a global manufacturing network where it is possible to configure more than one product per order. Nevertheless, the application environment is case specific and must be modelled dependent on the product being configured. In this research, the application environment is a site for wind turbines which performance in principle could be modelled in the same way as e.g. a harvester. The model is validated with data from a company selling capital goods and compared with best practices.
The potentials for implementing RMS and thereby reduce supply constraints are company specific. Potentials i.e. regarding size and weight are only for large capital goods, while potentials for i.e. complying with local content requirements only apply for companies bound by these requirements, etc.

4.2.2. INDUSTRIAL IMPLICATIONS

Stage configuration is not only a concept for product configuration, but rather an approach to align configuration activities from product development to product configuration, and from initial business case creation based on an opportunity to final order commitment and production. In this regard, the solution space modelling stages are aligned with product specification stages in product lifecycle management to potentially reduce time to market, reduce offering risks, increase sales, gain first-mover advantages, reduce internal complexity, and support shareability and transparency of the product families. To achieve these benefits, product families must be modelled to support stage configuration. Thereby, the company can potentially reduce the time for quotations and improve the quality by increasing product family transparency by only allowing specifying certain product characteristics when needed, rather than requiring a fully specified product variant to complete downstream supply processes.

The optimization model further enables supply chain planning to be proactive in the early stages in the order capturing process instead of reactive in the late stages. The model can potentially reduce lead time for business case creation, increase order intake from tenders, reduce risk of misaligned demand and supply, and reduce countless iterations between sales, supply, and product configuration.

4.3. FUTURE RESEARCH

The research presented in this thesis opens several viable future research directions:

- *Include engineering-to-order and uncertainties in optimizing product selection:* The suggested optimization model does not include products outside the standard solution space, which may be able to optimize order profitability even more, thereby incorporating automatic design. Supply chain decisions such as increasing capacity, altering the manufacturing footprint or changing current production and demand plans appear valuable to incorporate in the optimization model alongside dynamic changes to the application environment.

- *Allowing product configurators to specify product characteristics in stages:* Both on the variant configuration and the tooling side of product configuration, further investigations of how a stage-wise commitment of order specification can be allowed appears worthwhile. Variant configuration should for instance allow partly specified product characteristics to be applied to the configurable generic BoM and the configurator should allow for instance deselection of characteristics values. Potentially, this future research stream would increase the possibility for implementation of the concept of staged configuration.

- *Enabling downstream processes to work with partially specified BoMs:* Downstream processes such as planning, costing, quotation, capacity allocations, etc. are in industry rarely completed without an entire specified BoM, e.g. material requirement planning (MRP). Estimation methods with transparent uncertainties must be developed and capabilities of PLM and ERP systems must advance to aggregate between forecasted, firm, and uncertain requirements within the generic BoM used by supply chain processes.

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